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PALEOMAGNETISM AND PALEOGEOGRAPHY OF CRETACEOUS NORTHERN ALASKA

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PALEOMAGNETISM AND PALEOGEOGRAPHY OF CRETACEOUS NORTHERN ALASKA

A

THESIS

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By

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PALEOMAGNETISM AND PALEOGEOGRAPHY OF CRETACEOUS

NORTHERN ALASKA

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ABSTRACT

High biologic productivity, indicated by the enormous arctic Alaskan coal deposits of Late Cretaceous age, combined with the plant megafossils of those deposits suggest they were not formed at polar latitudes. These observations are in conflict with conventional paleogeographic reconstructions based on paleomagnetic data from the North American craton and the assumption that arctic Alaska was fixed with respect to North America by Late Cretaceous time. These reconstructions put arctic Alaska within a few degrees of the pole at the time the coals were formed. Even with significant climatic warming, the low sun angle and long winters are probably incompatible with the paleobotanical observations. The results of a paleomagnetic study of the mid-Cretaceous Nanushuk Group show the sediments were deposited at approximately 74° paleolatitude--significantly less than many reconstructions would indicate. Rotational and non-rotational tectonic models of arctic Alaskan tectonic evolution are evaluated in light of these observations.

CONTENTS

LIST OF FIGURES cont'd.

LIST OF FIGURES

LIST OF FIGURES cont'd.

LIST OF TABLES

Acknowledgements

The work for this thesis was supported by grants from Arco Alaska and the National Science Foundation (# EAR 78-00817). Additionally, Arco Alaska generously provided the field support which made the collection of the paleomagnetic samples possible. In particular the cooperation of Mr. Pete Barker of Arco Alaska facilitated the field work. The original plan for this study was suggested by Dr. David B. Stone, from whom I drew considerable enthusiasm and encouragement. I am also indebted to numerous faculty and students of the University of Alaska Geology/Geophysics Program for a thoughtful initiation to the geologic and tectonic riddles of northwestern North America.

INTRODUCTION

Purpose

The purpose of this study was to investigate the paleogeography of northern Alaska during the Cretaceous period. The Cretaceous rocks of the Alaskan arctic coastal plain include one of the largest coal deposits of North America (Tailleur and Brosge, 1975). If arctic Alaska was fixed with respect to North America by Early Cretaceous time, as many theories of arctic tectonic evolution demand (Tailleur, 1973; Churkin and Trexler, 1980; Jones, 1980), then this huge coal deposit was apparently produced at paleolatitudes of 85 degrees or greater. This high paleolatitude estimate leads one to question whether arctic Alaska was in place by Early Cretaceous time.

As the details of the new global tectonics have been explored it has become obvious that the Earth's geologic history cannot be completely explained by the movement of only seven rigid plates. During the past decade the notion that much of the western North American Cordillera is a collage of accreted allochthonous terranes has gained general acceptance (Beck *et al.*, 1980; Coney *et al.*, 1980). The basic elements of tectonic collages, *tectonostratigraphic terranes*, are defined as "fault bounded geologic entities characterized by a distinctive stratigraphic and/or a structural history differing markedly from those of adjoining neighbors." (Beck *et al.*, 1980). A tectonostratigraphic terrane is distinguished from a microplate in that the latter rides upon its own slab of lithosphere--tectonostratigraphic terranes need not be bounded by faults which extend down to the asthenosphere (Beck *et al.*, 1980).

Large scale and disparate northward motions have been proposed for most of the tectonostratigraphic terranes of southern Alaska and western Canada (Packer and Stone, 1974; Hillhouse, 1977; Stone, 1977; Jones et al., 1978; Coney et al., 1980; Monger and Irving, 1980). One of the consequences of the overall collage hypothesis for the formation of southern Alaska as proposed by a number of authors (Stone, 1977; Jones and Silbering, 1979; Stone and Packer, 1979) is that there is no obvious piece of "ancestral" Alaska. One of the few pieces of Alaska that can possibly be tied to the rest of North America is the Tindir area near the Yukon River/Canada border (Figure 1). The remaining tectonostratigraphic terranes forming interior Alaska have yielded little evidence of their place of origin or time of arrival.

Due partially to the incomplete assembly of the tectonic elements of Alaska and also to a partially closed Atlantic, the proto-Arctic Ocean was probably much wider in late Early and early Late Cretaceous time. It is conccivable that there was motion of an oceanic plate from the proto-Pacific into the proto-Arctic as indeed has been proposed by several authors (Churkin and Trexler, 1980; Jones, 1980). One main purpose of this study was to evaluate the relative merits of these northward drift models and the conventional counter-clockwise rotation model for arctic Alaska (Tailleur, 1973; Newman et al., 1977).

Research Avenues and Description of Field Area

Thesis investigations took two main avenues: A paleomagnetic study of Cretaceous sediments of northern Alaska and a paleontologic

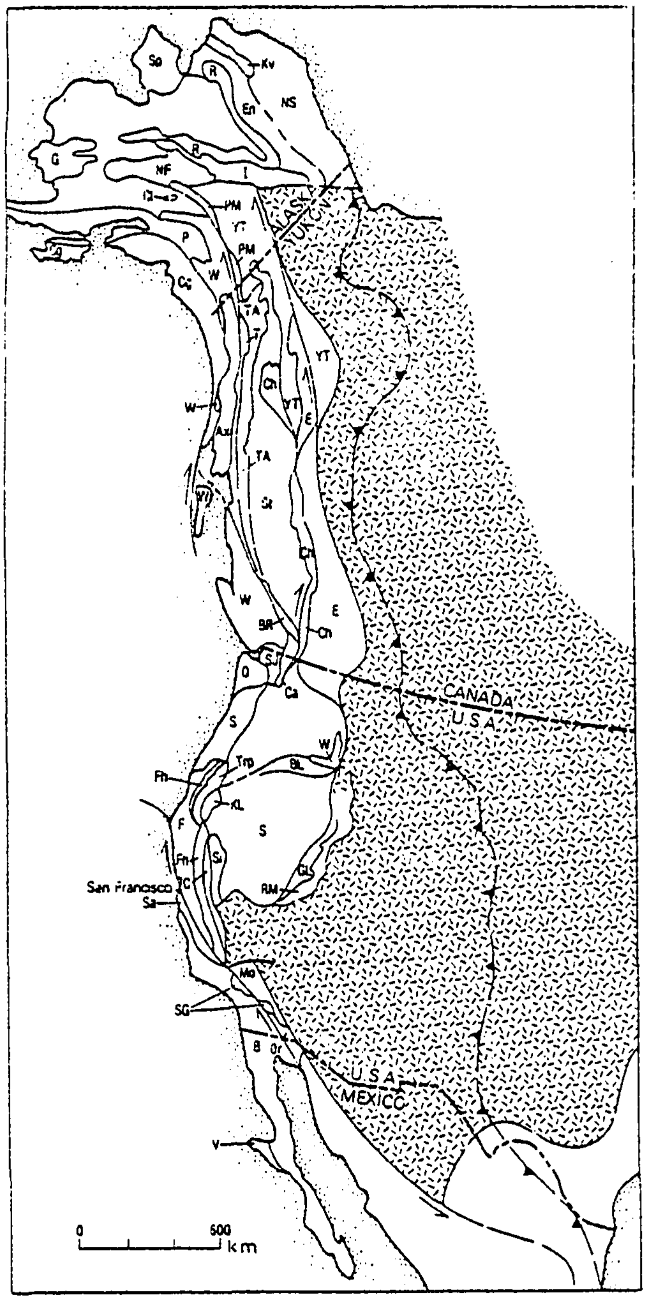


Figure 1. Generalized tectonostratigraphic terrane map of the western North American Cordillera. Only the shaded part of Alaska has definite ties to North America.
Key: Sp=Seward Peninsula, Ns=North Slope, Kv=Kagvik, En=Endicott, R=Ruby, I=Innoko, NF=Nixon Fork, G=Goodnews, Cl=Chulitna, PM=Pingston & McKinley, YT=Yukon-Tanana, W=Wrangellia, P=Peninsular, Cg=Chugach, Ax=Alexander, T=Taku, TA=Tracy Arm, Ch=Cache Creek, BR=Bridge River, St=Stikine, E=Eastern Assemblage, SJ=San Juan, Ca=Northern Cascades, O=Olympic, S=Sediments of the western Cascades, BL=Blue Mountain, Fh=Foothills, Trp=Triassic and Paleozoic of the Klamath Mountains, KL= Eastern Klamath Mountains, Si=Northern Sierra, C=Calaveras, F=Franciscan, Sa=Salina, SG=San Gabriel, OR=Orocopia, Mo=Mohave, B=Baja, V=Vizcaino, S=Sonomia, GL=Golconda, RM=Roberts Mountain. From Coney et al., 1980.

review of the plant megafossils found preserved in those sediments.

Paleomagnetic and paleontological samples were taken within the extreme western Brooks Range foothills province and the western arctic coastal plain from Cape Lisburne in the West to the Kokolik River in the East (see Figure 2). It is a region of subdued rolling hills which rise from the poorly drained tundra, swamps, and lakes of the arctic coastal plain. The gentle east-west trending folds of the region have strongly controlled the topography. The gentler synclines often form resistant ridges or isolated plateaus of considerable (approximately 200 meters) vertical relief although the apex-faulted anticlines are often eroded and occupied by streams. While the more resistant sandstones and siltstones crop out along the crests of ridges, the intervening shales are only exposed in the stream cut banks of actively meandering rivers. Except along protected draws vegetation is generally limited to grasses and sedges allowing excellent views of the outcrops from the air and on the ground. Dependably good outcrops with in situ rocks exposed are only found along the major stream courses, however.

Field studies were based out of the Arco Alaska Eagle Creek Camp approximately 150 air miles north of Kotzebue. Many of the sites sampled would be accessible by riverboat out of Cape Lisburne but helicopter support allowed a more complete and quickly executed sampling program. Further work in the region could be fairly easily accomplished by riverboat or Zodiac raft.

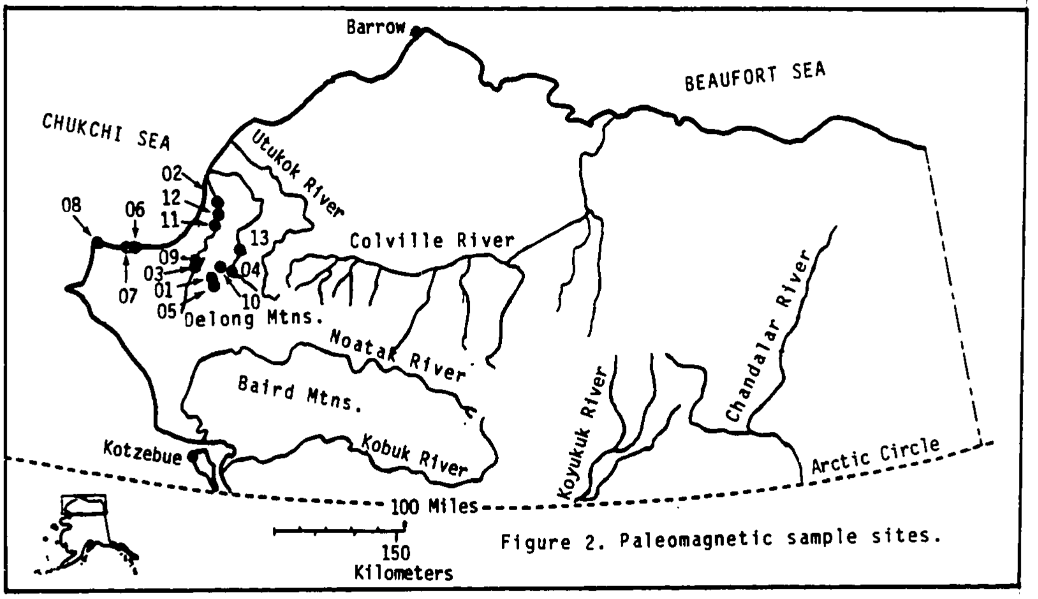


Figure 2. Paleomagnetic sample sites.

PREVIOUS WORK

Northern Alaska geology was almost wholly unknown until the beginning of this century. Early explorers and whalers reported the occurrence of oil seeps and coal along the Beaufort Sea Coast but it was not until 1901 that Schrader and Peters made the first topographic and geologic traverse from the Brooks Range across the Arctic Coastal Plain to the Beaufort Sea. In 1921 the Standard Oil Company investigated the Cape Simpson oil seeps. At that time however, there was oil to be found in much more hospitable regions of the United States and so the northern Alaskan province was reserved for future federal exploitation by Warren Harding as the Naval Petroleum Reserve No. 4. Initial results of geologic study of that region were published by Smith and Mertie (1930). This was the first complete geologic study of the region, and formed the basis of most later geologic studies in northern Alaska. U.S. Geological Survey Professional Paper 303-C (Chapman and Sable, 1960) not published until 1960, provided the basic geological background for the area of this study.

Recently, U.S. Geological Survey circular 794 (Ahlbrandt, 1979) reported the results of detailed petrographic and paleontological studies of the Nanushuk Group rocks with particular reference to their reservoir and source rock potential. In 1966 C.J. Smiley went to northern Alaska to study the plant megafossils and amber of the Cretaceous Nanushuk and Colville Groups. Smiley described the intriguing Cretaceous floras of northern Alaska in a series of papers (Smiley, 1966, 1967, 1969a, 1969b, 1976; Scott and Smiley, 1979).

GEOLOGIC FRAMEWORK OF NORTHWESTERN ALASKA

Pre-Brookian Historical Geology and Sedimentation

The oldest rocks of northern Alaska are from the Middle and Upper Devonian Neruokpuk Formation (Brosge and Tailleur, 1971). In the Romanozof Mountains these rocks, limestones and sandstones metamorphosed to lower greenshist facies, are truncated by the same angular unconformity that overlies the pre-Mississippian argillite basement found in the subsurface of the coastal wells. In the Delong Mountains of the western Brooks Range the base of the Mississippian System lies conformably within the Upper Devonian and Lower Mississippian Endicott Group (Figure 3).

Above the Endicott Group the shallow water carbonates of the Lisburne Group are time-transgressive across the Brooks Range (Brosge and Tailleur, 1971; Mull *et al.*, 1982). To the west, in the vicinity of the study area, the Lisburne Group is upper Lower and Upper Mississippian in age while to the east the Lisburne is Upper Mississippian to Lower Permian in age. The Lisburne and nearly all the higher Paleozoic and lower Paleozoic rocks pinch out to the North at about the present Arctic Ocean coastline. This truncation is in part depositional but is probably also the result of a Late Mesozoic unconformity. The direction of transgression of the Lisburne Group was northward up onto a height of land known as the Barrow Arch.

Conformably in the West, and disconformably in the East, the Etivluk Group (Mull *et al.*, 1982) overlies the Lisburne Group. Of Pennsylvanian to Upper Jurassic age, the Etivluk Group consists

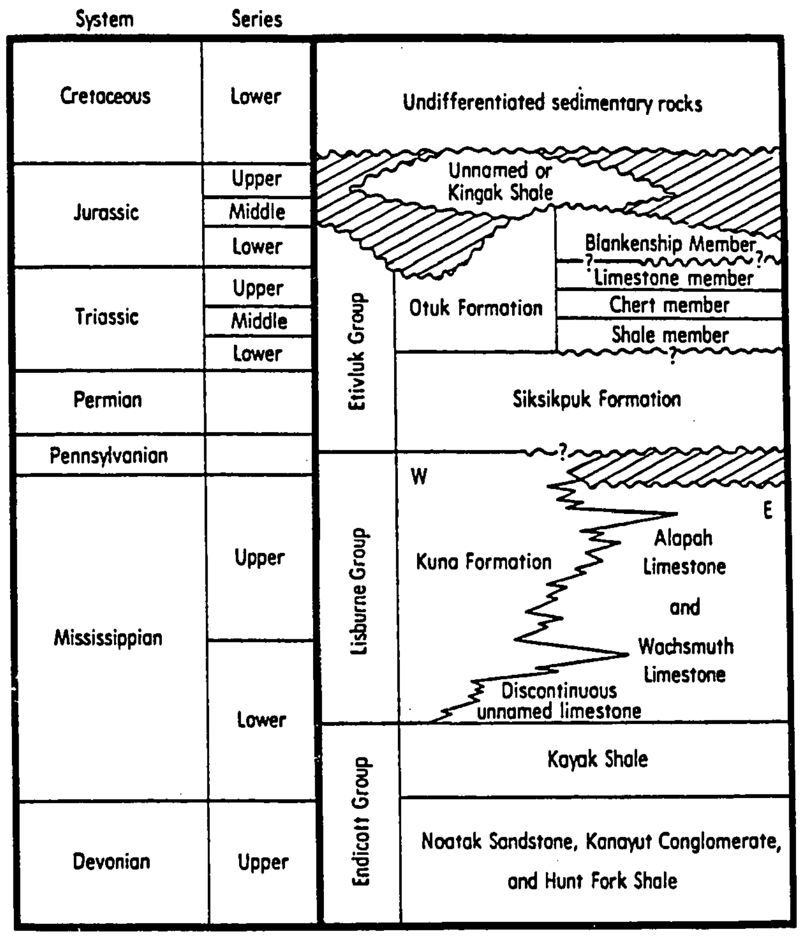


Figure 3. Pre-Cretaceous stratigraphy of the western and central Brooks Range. From Mull et al., 1982.

of the Siksikpuk and Otuk Formations (the Shublik Formation of the western Brooks Range has been renamed the "Otuk Formation" in the study area (Mull et al., 1982)). The Etivluk represents yet another northward marine transgression onto northern Alaska. The Upper Triassic Otuk Formation marks a transition to deeper water facies from the shallow platform deposits of Mississippian through Permian time. The source of the Otuk Formation sediments remained to the northeast as demonstrated by the presence of nearshore clastics in Otuk equivalent rocks in the northeast Brooks Range.

The Jurassic aged Kingak Formation, a thick pyritic shale in the Northeast, is represented only by a thin unnamed shale, chert, and basalt unit in the West. The Upper Jurassic-Cretaceous boundary is arbitrarily set by many workers (e.g., Brosge and Tailleur, 1971) at the base of the distinctive pebble-shale unit that unconformably truncates the Jurassic shales.

It is only in the Early Cretaceous Okpikruak Formation, a unit that achieves its best definition in the western Brooks Range, that one sees a shift from predominantly northern sediment sources to southern sediment sources. It is this shift in source direction that presumably marks the beginning of the collisional Brookian orogeny and uplift.

Post-Brookian Historical Geology and Nanushuk Group Sedimentation

With the onset of the Brookian Orogeny during Neocomian time the deep sedimentary basin of the northern Alaska coastal plain saw an abrupt and radical shift in sedimentary provenance and paleotransport direction. Uplift of the Brooks Range caused a thick sedimentary wedge to prograde across the Colville trough from south to north. In most places the lowest rocks of this sedimentary wedge are of the Fortress Mountain Formation; a dark, shaly, flysh sequence that coarsens southward to a conglomeratic sequence. Above these bottomset beds and partially included as bottomsets themselves are the silty shales and turbidites of the Torok Formation. Figure 4 shows the fairly steep foreset beds (up to 6 degrees original depositional dip) of the Torok Formation. The upper part of the Torok Formation represents a fairly shallow-water facies with perhaps local unconformity in the vicinity of the Meade Arch, east of the Utukok River.

The Upper Cretaceous (Albian to Cenomanian) Nanushuk Group rocks, from which the majority of the paleomagnetic and paleontological samples were taken, represent the topset beds of the prograding sedimentary prism that built out generally northeastward from the Brooks Range uplift. The Nanushuk consists of two well defined sedimentary formations in the study area (Figure 5). The Kukpowruk Formation represents a largely marine facies with interbedded foreshore sands and bars. The Corwin Formation is the nearshore and terrestrial equivalent of the Kukpowruk. Both formations are time-transgressive. An isopach map (Figure 6) of the Nanushuk Formation indicates the southwesterly source of the Nanushuk Group sediments. The Corwin Delta system of the western North Slope was responsible for the complexly intertongued marine and terrestrial stratigraphy in the study area. The Umiat Delta was formed

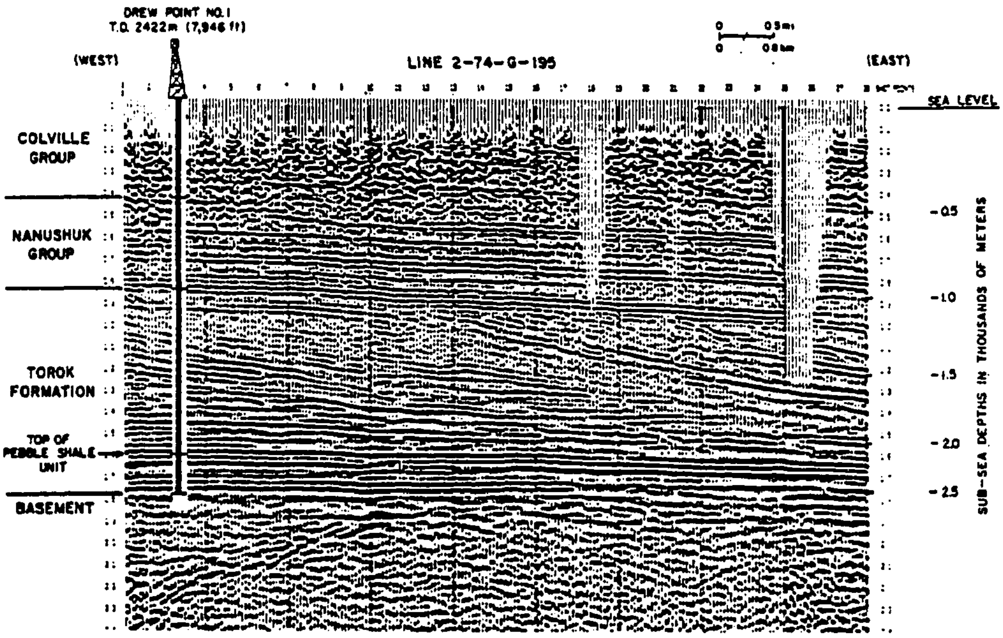


Figure 4. Seismic depth section correlated with stratigraphy from the Drew Point no.1 well. Note the fairly steep foreset beds (up to 6° original dip) in the Torok Formation. Nanushuk rocks have comparably smaller orginal dips as shown in this section. Location of Drew Point no.1 well and seismic section shown on Figure 6. From Ahlbrandt, 1979.

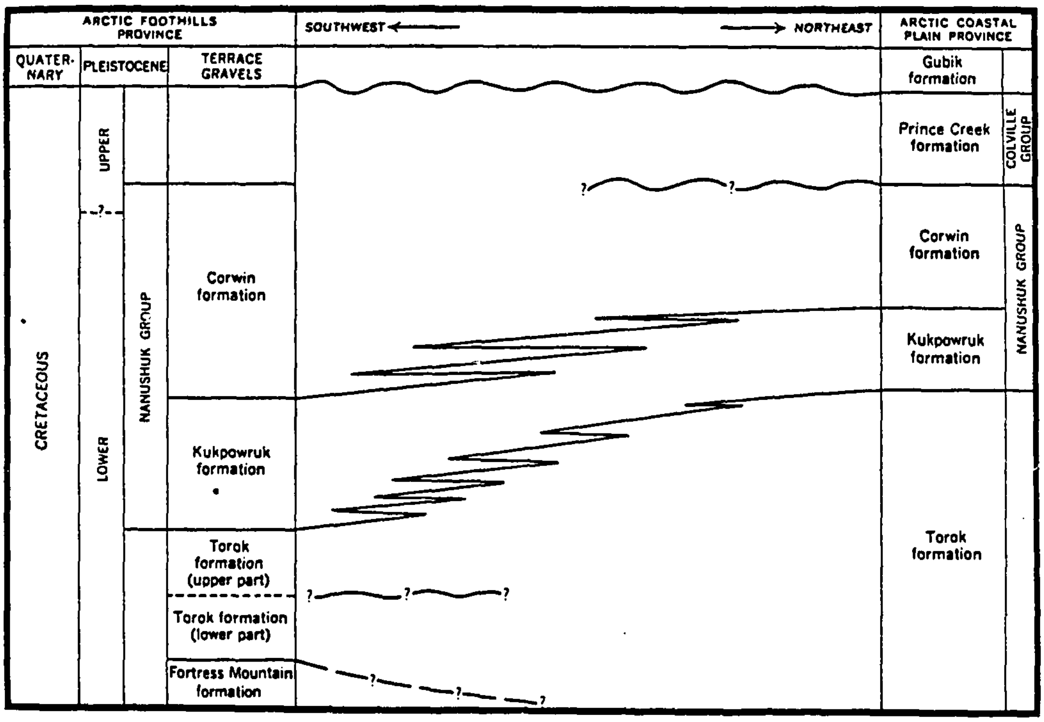


Figure 5. Cretaceous stratigraphy in the study area. From Chapman and Sable, 1960.

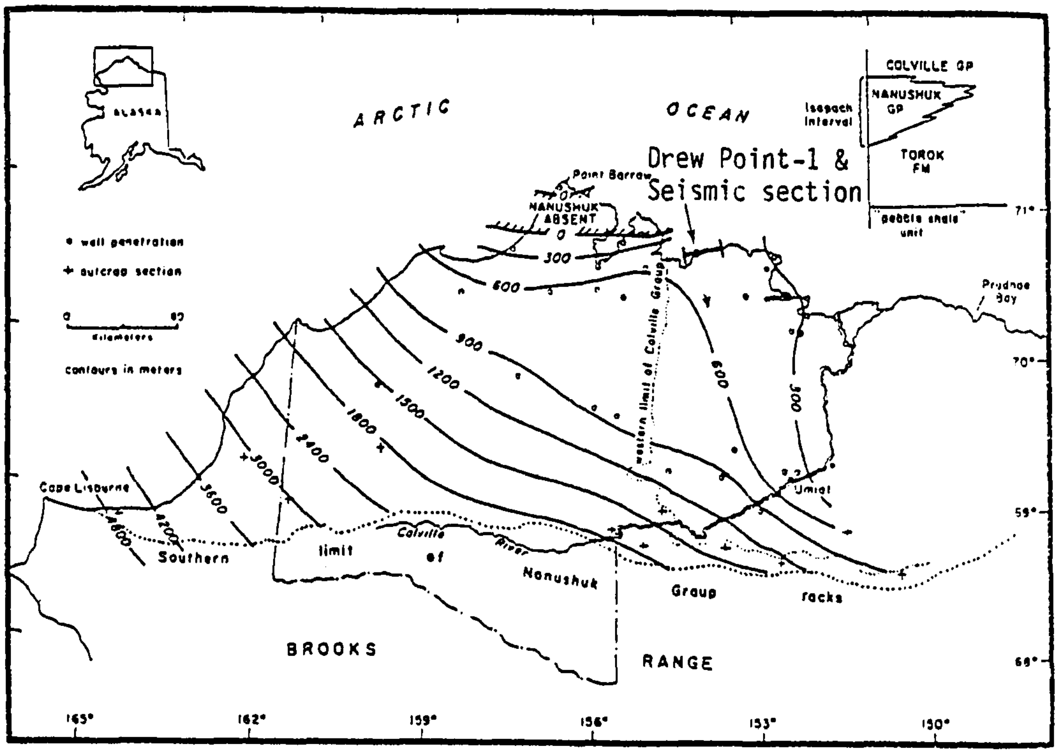


Figure 6. Isopach map for the Nanushuk Group showing the thickening of the sedimentary wedge to the southwest. From Ahlbrandt, 1979.

by another similar system operating to the east. The Colville Group represents another later (Turonian and Senonian) Late Cretaceous marine transgression which onlapped in much the same manner as the Nanushuk transgression but to a lesser extent.

Rocks from the Tertiary of northern Alaska are the predominantly terrestrial Sagvanirktok Formation and the marine Nuwok Formation which attained considerable thickness north of the Sadlerochit Mountains but are generally absent in the study area.

PALEOMAGNETISM

The Geomagnetic Field

The technique of paleomagnetism depends on the preservation of the geomagnetic field from the past in the presently available rock record. The interpretation of this remanent field along with assumptions about the nature of the past geomagnetic field has allowed paleomagnetists to speculate on large-scale lithospheric movements. It behooves paleomagnetic workers to thoroughly understand both the Earth's geomagnetic field and how the rock record preserves that field.

The natural remanent magnetization of minerals has been used for over twenty centuries as a navigational tool, however only within the last 300 years have we begun to understand the geomagnetic field. The Chinese used naturally magnetic magnetite in lodestone as the active element of compasses as early as 200 B.C.. The mysterious properties of the lodestone were often ascribed supernatural causes (McElhinney, 1973). It was not until 1600 A.D. that William Gilbert first described the geomagnetic field as an axial dipole. The geomagnetic field is generally recognized to be the result of a self-exciting dynamo process within the electrically conducting liquid outer core of the earth.

The average magnitude of the geomagnetic field over the surface of the Earth today, .31 oersteds, gives an estimate of 8.06×10^{25} oersteds - cm^3 for the Earth's dipole moment (Irving, 1964). The field is approximately dipolar with the axis tilted 11 degrees from the rotation axis and slightly displaced from the center of the Earth. Whatever specific dynamo process is considered responsible for the Earth's field, it must be consistent with several interesting observations of the field and its time variations.

Principal among these observations are the existence of the Earth's field since at least 3.5 billion years before present, the phenomenon of field reversals (with a mean length of 0.22 million years over the last ten million years), the postulated 10-12000 year period for the westward drift of the main field, and the 2000 years or less that it takes for a reversal to occur. Several other periodicities on the order of 100-4000 years constitute the "non-dipole secular variation field". These variations with generally smaller spatial and temporal periods are often attributed to shallower sources in the core, just below or involving the core-mantle boundary. For studies such as the Arctic study described below, these variations are assumed to be averaged out if random samples are taken over a sufficiently long period of time, commonly estimated at a few tens of thousands of years. Cox (1975) points out that this may not be true if the secular variation field is caused by core-mantle interactions with zonal symmetry (Figure 7).

Based on data from Hawaiian basalts, Cox (1975) suggested that secular variation produced a statistical bias toward shallower inclinations at low latitudes (less than 40 degrees) and a bias towards steeper inclinations at high latitudes (greater than 40 degrees). This bias apparently never amounts to more than 5 degrees of inclination error. It is encouraging to note that this inclination error is opposite in sign to the inclination anomaly often observed in paleomagnetic studies from the western North American Cordillera and commonly ascribed to northward drift of blocks and slivers of what is now North America.

Remanent Magnetization

Only a few minerals are significantly magnetic to contribute to the remanent magnetism of a rock. Most of these are part of the iron, titanium oxide system: $FeO-TiO_2-Fe_2O_3$.

Only a small percentage of the minerals in a rock are ferro- or ferrimagnetic and contribute to the net magnetic remanence of a rock sample. The manners in which these magnetic grains align their magnetic moments to produce a net remanence are many and varied, however only three are of importance to this study.

Detrital Remanent Magnetization or DRM is the remanent magnetization acquired by sedimentary rocks during deposition and diagenesis. Even compositionally mature sediments have a small percentage of ferromagnetic grains, these grains tend to align their magnetic moments along the

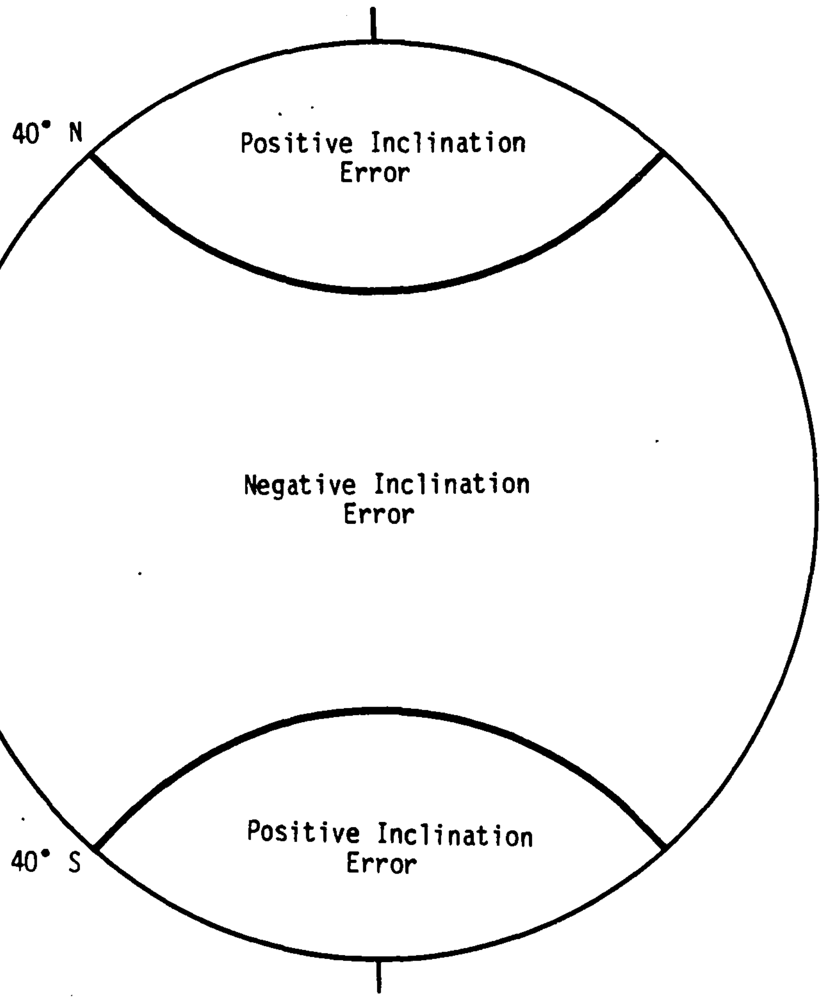


Figure 7. Inclination anomaly associated with zonal non-uniformity in the occurrence of westwardly drifting magnetic anomalies.

main field while in suspension. Assuming no systematic rotation is induced at the moment of deposition, the deposited grain will be preserved in alignment with the main field at the time of deposition (Nagata, 1961). This component of DRM is termed depositional detrital remanent magnetization (dDRM) (Verosub, 1977). Numerous studies have examined inclination errors which are developed during the preservation of dDRM (King, 1955; Griffiths et al., 1960; Collinson, 1965; King and Rees, 1966) but Irving (1957) has pointed out that even in the case where magnetic carriers are deposited with spurious or even systematically incorrect orientations they may remain free to realign due to Brownian agitation in fluid-filled pore spaces. The magnetic grains, owing to their higher densities, tend to be smaller than the other grains deposited in a given flow regime and will often occupy the interstitial spaces of the sediment after deposition and during diagenesis. Up until the time the magnetic grain is cemented in place it is free to rotate and realign with the geomagnetic field. This realignment of magnetic carriers after deposition is termed post-depositional detrital remanent magnetization or pDRM. Studies to determine the extent and properties of pDRM (Irving and Major, 1964; Løvlie, 1974, 1976; Tucker, 1979; Barton et al., 1980; Payne and Verosub, 1982) have concluded that Irving's physical model is basically correct and indicate that some fraction of nearly all the magnetic carriers are mobile at high fluid contents. Payne and Verosub (1982) determined that sediments with sand contents of 50-60 percent or greater are easily remagnetized while the pore spaces remain fluid filled (R-type sediments) but finer grained sediments (S-type) are stabler with regard to remagnetization (Figure 8).

Petrographic study of Nanushuk Group sandstones (Ahlbrandt, 1979) indicated the modal grain size to be approximately 0.1-0.3 mm with less than 30 percent of the rock consisting of cement plus matrix (Figure 9). This range of grain sizes and ratio of matrix minerals (clays) to clasts indicates the Nanushuk sediments should be R-type sediments. Depositional inclination errors should be small due to a large component of pDRM. Compaction and dewatering were obviously post-depositional and at least pre-folding as indicated by the positive fold test from WNS-12. Because the carriers were probably realigned shortly after deposition and before folding the Nanushuk Group sandstones should be reliable indicators of the geomagnetic field during or slightly after deposition.

Thermal Remanent Magnetization or TRM is the remanent magnetization acquired by the heating of the magnetic carriers in an external field, and is the origin of the magnetization in the grains aligned in DRM. The Curie Point is the temperature at which thermal agitation of the magnetic moments in the crystal lattice makes it impossible for a significant number of magnetic moments to align and stay aligned. The Curie Point is an intensive quantity of a specific mineral of a specific chemical composition. It does not depend upon the size or shape of the magnetic carriers. The magnetic grains of real rocks are often of dimensions such that the size and shape of the grains begin to modify their ability to maintain alignment of their moments.

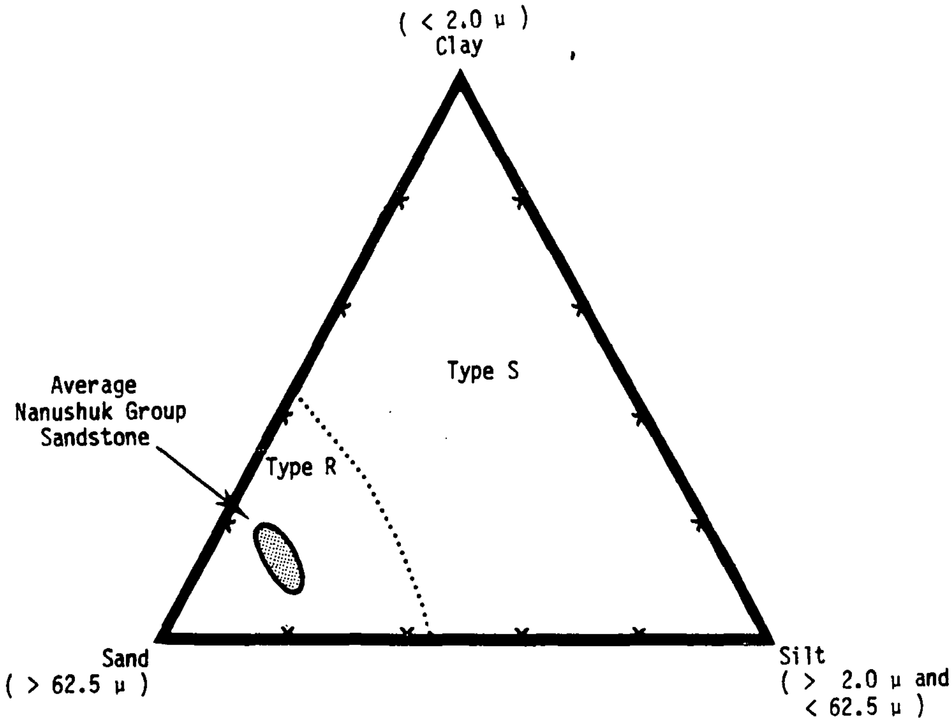


Figure 8. Sediment classification of Payne and Verosub (1982). R-type sediments usually carry a large component of pDRM (post-depositional detrital remanence), while in S-type sediments the dDRM (depositional detrital remanence) is generally stable.

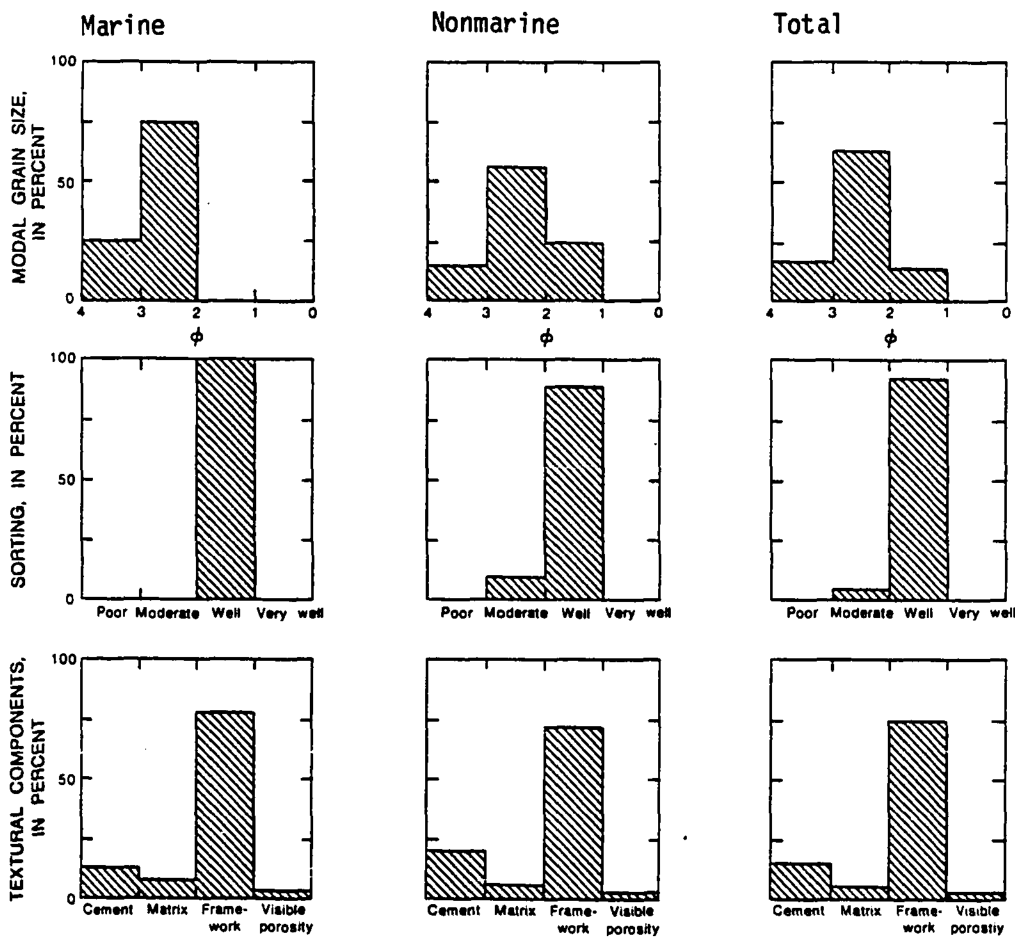


Figure 9. Modal size and size sorting as well as percent framework, cement, matrix, and visible porosity of Nanushuk Group sandstones. From Ahlbrandt, 1979.

In a typical rock the magnetic carrier size and composition will both cover a range of values and thus the Curie Point will not be a single temperature but rather a "blocking spectrum".

Isothermal Remanent Magnetization or IRM is simply the magnetization acquired by the sample due to the spontaneous alignment of magnetic moments with the ambient field at constant temperature. An isothermal remanence which has been acquired over a long time will require a field much larger than that which produced the remanence in order to realign the affected carriers. This apparently "harder" remanence is termed viscous remanent magnetization (VRM) and is one of the primary sources of noise in paleomagnetic data.

The observed remanent magnetism of a rock may differ from the original magnetization generated during deposition and diagenesis for several reasons. The thermal history of the sediments might include one or several thermal pulses that brought the rock into conditions under which some of the magnetic carriers had significantly shorter relaxation times. If the dipole moment of the Earth or the position and orientation of the sediments had changed between the time of deposition and the time of the thermal spikes, a TRM will be impressed on the rocks. The observed magnetization may also differ from the original due to a VRM component.

Fortunately the magnetic carriers in a rock are not all exactly alike. Neither their size, shape, chemistry, nor crystallography are identical--rather each of those variables covers a range of values. For this reason it is possible to remove the effect of the more easily realigned carriers by randomizing them and then measuring the remaining "harder" magnetic component. However, it is possible that none of the original remanence remains; in this case some usable information might still be extracted but interpreting orientation information and the dating of the remanence is problematic.

Demagnetization Results

The remanent magnetization of most rocks can be realistically modeled as the contribution of many non-interacting single domain grains. For single domain grains the relaxation time, τ, is related to coercivity, saturation, magnetization, and temperature thusly:

$$\tau \propto e^{\frac{vH_cJ_s}{2kT}}$$

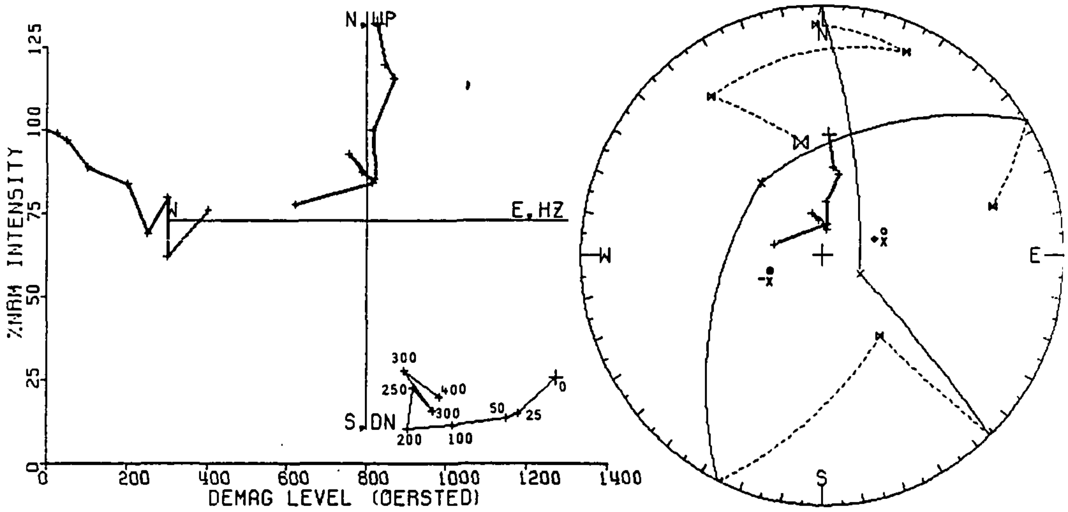
where v is the volume; Hc, the coercivity, is the field necessary to just overcome the remanent magnetization; Js is the saturation magnetization; k is Boltzmann's constant; and T is the absolute temperature (McElhinney, 1973). The relaxation time can be thought of as an indication of the stability of the remanence. Grains with large relaxation times will preserve a primary DRM or TRM better than those grains with short relaxation times. A typical rock will contain many magnetic carriers with different relaxation times. Clearly for the purpose of paleomagnetic studies the grains with the longest relaxation times are the most interesting. The equation above shows that the short relaxation time grains will be those with low coercivity. In order to exploit this relationship As and Zijderfeld (1958) proposed the process of alternating field (AF) demagnetization. The method has been variously improved over the years but generally consists of subjecting a sample to an alternating field that randomly and uniformly varies in direction while its intensity is slowly ramped-down from some peak value. By alternating this demagnetization treatment with remanence measurements while progressively increasing the peak alternating field this method allows a step-wise examination of the magnetization of grains with larger and larger relaxation times. Usually the grains of interest, those with relaxation times on the order of millions of years, are those isolated at the highest level of demagnetization. Not all rocks are amenable to this treatment, however. If the magnetic grains all have short relaxation times then a stable primary remanence will not be preserved and AF demagnetization will be fruitless.

AF demagnetization also will fail if the primary remanent magnetization is of comparable intensity with the Rotational Remanent Magnetization or RRM induced during demagnetization. RRM was first described by Wilson and Lomax (1972) but not until recently has a theoretical basis for the effect been published (Wilson, 1980; Stephenson, 1980a, 1980b, 1980c). Stephenson shows that RRM is a manifestation of the Barnett gyromagnetic effect. A rock rotating in field-free space will acquire a magnetization due to the alignment of its magnetic moments along the spin axis (Barnett, 1935). Barnett showed that this effect should not be measurable in field-free space unless the revolution rate is on the order of 10^6 r.p.s.. The gyromagnetic effect is significant in the case of RRM because the important time constant for a rotating rock in an alternating field is not the bulk rotation rate but rather the rate at which the magnetic domains flip polarity. A magnetic domain flips polarity in approximately 10^{-7} second or faster (Stephenson, 1980a). Thus the effective rate of rotation, the rate at which the domains flip, is such that the axially directed gyromagnetic field is on the order of 1 millitesla or about that demanded to introduce RRM.

Figure 10 shows the AF demagnetization of sample WNS-02-02C. The sample was loaded in the demagnetizer such that RRM would be expected along the -x axis. The -x axis and +x axes are indicated in Figure 10. After treatment at 300 Oersteds RRM was suspected, the sample was reloaded such that RRM would be expected along +x. Retreatment and remeasurement confirmed the hypothesis that a strong RRM component was present with an intensity of approximately 1.5×10^{-7} EMU/cc.

The RRM effect was encountered in most of the samples during AF demagnetization at the 300 Oersted level. Attempts to mitigate RRM by demagnetization twice with the x axis parallel and antiparallel to the rotational vector of the inner tumbler axis were unsuccessful. Largely for this reason the AF demagnetized samples were considered unstable and not included in the statistical analysis.

Thermal demagnetization was, however, successful and yielded stable magnetic directions for the bulk of the samples. Thermal demagnetization involved heating the samples to progressively higher



Depth 0.00 | Azm Core: 21.0 | Dip Core: 28.0 | Skw Core: 0.0 | Azm Bed: 355.0 | Dip Bed: 50.0 | Site Lon: 197.20 | Site Lat: 69.50 | Vol(cc): 10.00 | Suscept: 0.00 | Demag Type: AF | Spec Demag: none | Reversed: No | Zid: Strat | Mag: Strat | Diff: Strat

Demag level oe	Date	Tol %	Intensity EMU/cc	% NRM	Magnetization Vectors Geo <DIR> Dec	Inc	Strat Dec	Inc	Geo <VGP> Lon	Lat	Strat Lon	Lat	Intensity EMU/cc	% NRM	Difference Vectors Geo <DIR> Dec	Inc	Strat Dec	Inc	Geo <VGP> Lon	Lat	Strat Lon	Lat
0	12 Jan 82	2	2.15E-07	100	76	83	3	39	234	69	13	42										
25	12 Jan 82	2	2.13E-07	99	141	76	7	51	220	46	8	52	4.64E-08	22	350	9	349	-41	28	25	27	-3
50	12 Jan 82	1	2.09E-07	97	141	72	11	54	223	40	1	54	1.50E-08	7	320	29	324	-14	63	31	53	10
100	12 Jan 82	3	1.91E-07	89	167	63	4	66	207	25	10	69	4.91E-08	23	31	36	23	-7	340	37	353	15
200	12 Jan 82	1	1.81E-07	84	170	51	11	78	206	11	306	86	4.13E-08	19	359	45	339	-5	18	47	19	18
250	12 Jan 82	1	1.49E-07	69	176	56	354	74	201	16	35	80	3.71E-08	17	156	29	115	70	221	-4	243	43
300	12 Jan 82	0	1.73E-07	80	182	59	344	70	196	20	50	73	2.79E-08	13	60	-66	144	-46	333	-36	243	-43
300	12 Jan 82	7	1.33E-07	62	169	54	9	75	204	14	345	82	4.68E-08	22	237	63	318	47	153	31	70	43
400	12 Jan 82	1	1.65E-07	76	206	43	282	67	174	6	119	49	7.49E-08	35	65	-4	74	-18	312	7	305	-3

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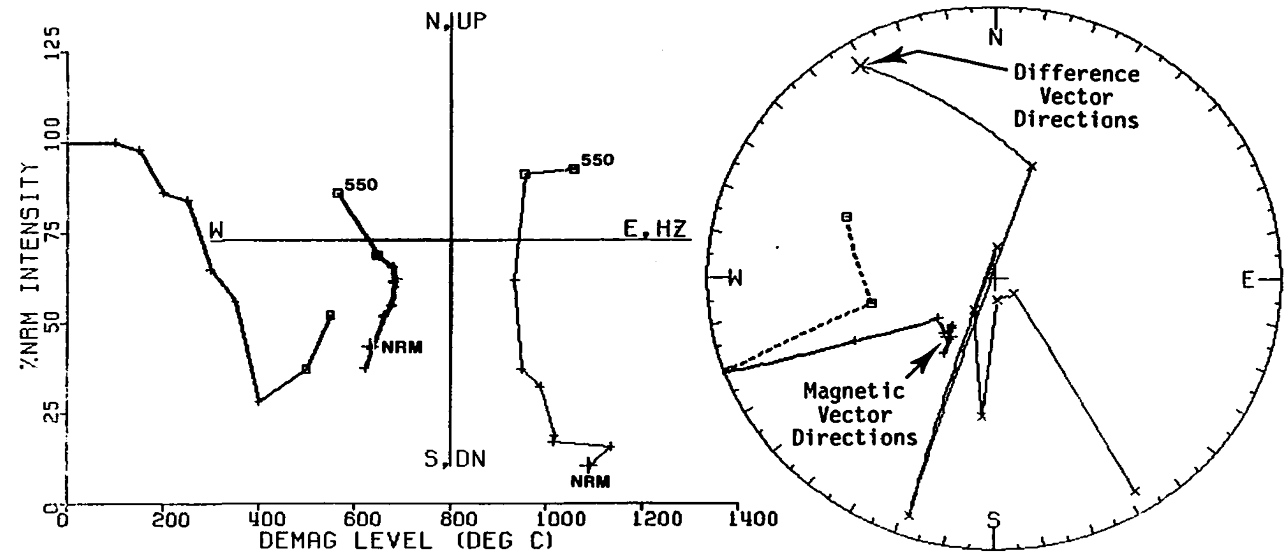
Figure 10. AF demagnetization of WNS-02-02c showing the vector direction and difference vector at each level, as well as -x and +x in the stratigraphic frame of reference.

temperatures in an electric furnace with fairly low internal fields and then removing the samples to a cooling area with essentially zero field. In practice the axial field in the cooling area was 12.0 milligauss. Samples were heated and cooled for approximately 15 minutes below 300° C. and 20 minutes above 300° C.

Thermal demagnetization depends on the principle that relaxation time is inversely related to temperature. As temperature increases the relaxation times of all the magnetic domains decrease (assuming again single domain non-interacting grains). Those grains whose relaxation times are short (on the order of 100 seconds) will randomize and remain randomly aligned in the field-free cooling area. In this way the contribution of the least stable magnetic grains will be reduced and the remaining magnetization of the specimen will be dominated by the stabler magnetic grains related to the original DRM.

In nearly all cases the method for selecting a stable magnetic vector during the demagnetization process was to pick the vector corresponding to the demagnetization level during which the direction changed the least. Figure 11 shows a typical thermal demagnetization run. The magnetization direction picked as the stable point for this sample was at 350° C.

Often at demagnetization levels greater than 500° C. a sharp increase in intensity and a radical shift in the direction of magnetization indicated a chemical reaction had taken place in the samples. After this chemical change sample magnetizations were considered meaningless. That a chemical change, probably the oxidation



Depth 0.00 — Azm Core: 199.0 — Dip Core: 11.0 — Skw Core: 0.0 — Azm Bed: 204.0 — Dip Bed: 50.0 — Site Lon: 195.00 — Site Lat: 68.90 — Vol(cc): 10.00 — Suscept: 0.00 — Demag Type: Ther — Spec Demag: none — Reversed: No — Zid: Strat — Mag: Strat — Diff: Strat

Demag level deg C	Date	Tol %	Intensity EMU/cc	% NRM	Magnetization Vectors Geo <DIR> Dec	Inc	Strat Dec	Inc	Geo <VGP> Lon	Lat	Strat Lon	Lat	Intensity EMU/cc	% NRM	Difference Vectors Geo <DIR> Dec	Inc	Strat Dec	Inc	Geo <VGP> Lon	Lat	Strat Lon	Lat
0	7 Jan 82	0	1.12E-06	100	8	69	215	60	357	73	167	23										
100	7 Jan 82	1	1.12E-06	100	9	69	214	60	355	74	168	22	1.18E-08	1	322	-22	329	6	52	5	48	21
150	8 Jan 82	0	1.10E-06	98	6	75	212	54	354	83	168	16	1.18E-07	11	19	-7	17	43	355	17	353	45
200	8 Jan 82	1	9.63E-07	86	9	64	220	64	0	67	165	29	2.42E-07	22	195	54	199	4	183	14	176	-18
250	9 Jan 82	1	9.41E-07	84	8	65	219	63	1	68	165	27	2.76E-08	2	19	27	4	77	353	34	354	85
300	9 Jan 82	0	7.30E-07	65	2	68	220	60	10	72	163	24	2.18E-07	19	21	55	211	75	345	55	175	42
350	9 Jan 82	0	6.27E-07	56	357	62	232	63	21	64	154	29	1.28E-07	11	124	74	185	36	231	45	191	-1
400	9 Jan 82	2	3.12E-07	28	295	58	244	34	98	45	136	8	3.89E-07	35	31	48	176	81	335	46	197	51
500	9 Jan 82	1	4.09E-07	37	240	-6	257	-43	132	-13	107	-28	4.57E-07	41	37	42	129	80	329	40	220	54
550	9 Jan 82	2	5.82E-07	52	269	-19	293	-31	103	-10	77	-8	3.11E-07	28	134	29	148	5	239	0	228	-16

3 A — NTHSLP E CORWIN **WNS-06** — 6 Feb 1982 — Paleomagnetic Laboratory, Woodward-Clyde Consultants

Figure 11. Typical thermal demagnetization run. The three plots show (left to right) percent NRM at each level, a modified Zijderveld diagram, and a stereographic plot of the magnetic vectors and the difference vectors.

of magnetite to hematite, had taken place was indicated by the change in color of the cores (Figure 12). Examination of the rocks in thin section shows the growth of red hematite at the expense of unidentified opaque grains (Figures 13 and 14). Demagnetization at temperatures greater than 450° C. should probably be attempted only in an inert atmosphere.

Statistical Methods

The remanent magnetization of a specimen can be expressed as a vector, a three-dimensional quantity with both direction and magnitude. The length and direction of the three-dimensional magnetization vector are commonly referred to three coordinate systems using both polar and rectangular coordinates. The conventions for the various frames of reference used in this study are detailed in Appendix A. The three main coordinate systems discussed here will be the core frame, the geographic frame, and the stratigraphic frame. The core frame is oriented with respect to the fiducial line and axis of the core. The core frame is usually only of direct interest when discussing measurement and demagnetization procedures. The geographic frame is tied to the field orientation of the sample, namely present horizontal and present true North. It is slightly artificial but is the proper arena for discussion of VRM and possibly late TRM. The stratigraphic frame of reference hopefully represents the orientation of the magnetic vector with respect to paleo-horizontal and paleo-North. The rotation assumed between the geographic and stratigraphic frames is the

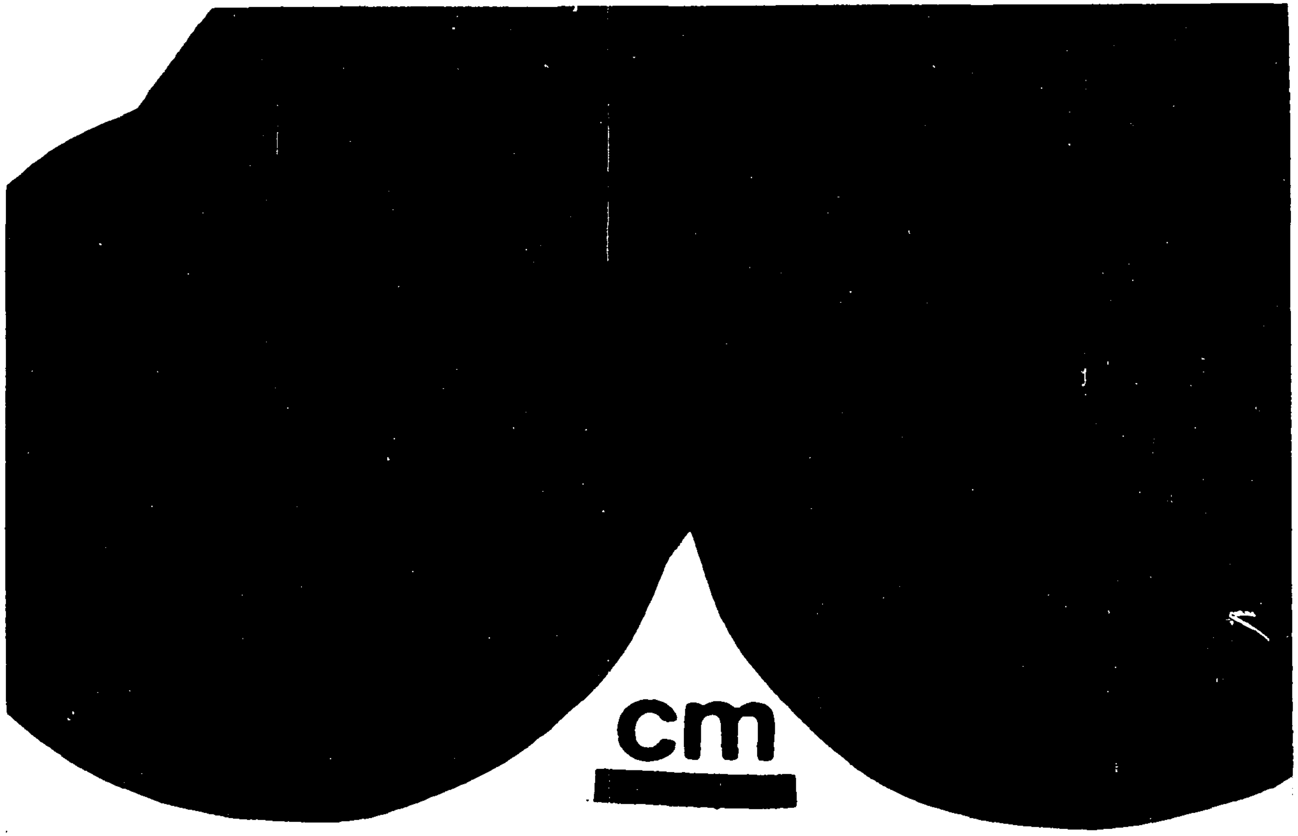


Figure 12. Macrophotograph of cross-sections of rock core before (right) and after (left) thermal demagnetization.

Figure 13. Photomicrograph of thin section of rock core before thermal demagnetization. Photomicrograph is in plane light.

Figure 14. Photomicrograph of thin section of rock core after thermal demagnetization. Photomicrograph is in plane light.

structurally simplest: a simple rotation around the present strike of some preserved plane of original horizontality such as bedding. The errors and assumptions involved in the transformation between these coordinate systems are discussed in the section on sampling.

PALEOMAGNETIC RESULTS

Sites Sampled

In order to further explore the paleogeography of the North Slope region 150 oriented cores were drilled from surface exposures of the Cretaceous Nanushuk Group of western arctic Alaska. The remanent magnetizations of these samples were measured as the cores were progressively demagnetized by both thermal and alternating field methods.

Sites sampled ranged from the Cape Lisburne and Corwin Bluff regions in the Northwest to outcrops along river cuts of the Kokolik River in the East (Figure 2). The sampling strategy employed was aimed at garnering as continuous a sample of the rock record representing the greatest length of time as possible. The gently folded and occasionally faulted structure of the Nanushuk Group in this area made it fairly easy to sample several thousand meters of the section without interruption. Table 1 shows the vertical section sampled, the number of samples, and location of the sites sampled in this study. Throughout, the nomenclature of Irving (1964) is used when discussing sites, samples and specimens (Table 2). To be considered significant, a site generally consists of at least seven samples,

Table 1

Paleomagnetic Sample Sites

Site	Vertical Section Meters	Original N	Location Long., Lat.
WNS-01	<10	4	197.4 , 68.7
WNS-02	425	14	197.2 , 69.5
WNS-03	975	8	196.8 , 68.8
WNS-04	30	8	197.9 , 68.8
WNS-05	15	4	197.5 , 68.6
WNS-06	300	10	195.0 , 68.9
WNS-07	610	12	194.8 , 68.9
WNS-08	<10	2	193.9 , 68.9
WNS-09	2050	12	196.8 , 68.9
WNS-10	45	7	197.7 , 68.8
WNS-11	625	17	197.3 , 69.2
WNS-12	190	21	197.4 , 69.4
WNS-13	170	14	198.1 , 69.0

Table 2

Nomenclature used with reference to

sites, samples, and specimens.

```
                                                   Specimen
                                                *     .
                                            *         .
                                        *             .
                              Sample*                (as many as 5)
                           *     .      *             .
                        *        .          *         .
                     *           .              *  Specimen
                   *             .
         Site*              (no less than 7)
                   *             .                 Specimen
                     *           .              *     .
   (e.g., WNS-01)       *        .          *         .
                           *     .      *             .
                              Sample*                (as many as 5)
                                        *             .
                        (e.g., WNS-01-01)   *         .
                                                *  Specimen

                                            (e.g., WNS-01-01A)
```

each sample yielding at least two and as many as five specimens.

Limits and Biases of the Sampling Method

The paleomagnetic rock samples were drilled with a diamond-tipped gasoline-powered core drill of fairly standard design. In all but a few cases the core was oriented while still attached to the rock. On short or poorly drilled cores the error in orientation could be as much as 5 degrees. Bedding planes were measured with a Brunton compass to determine ancient horizontal, however bedding planes are not always parallel to ancient horizontal.

A difficult problem encountered during sampling was the possible bias introduced in interpreting bedding planes as indicators of ancient horizontal. In a prograding system such as the Corwin Delta considerable original dip may be generated (Reading, 1978). Original dips would be in the direction of progradation. In the case of the Corwin Delta this is to the north-northwest. Thus vertical or north-northwesterly magnetic vectors would appear to be rotated toward shallower inclinations. This effect was recognized in the field and an attempt was made to mitigate it by measuring the azimuth and dip of the largest bedding features observed at outcrop scale and noting the presence or absence of sets of cross laminations.

Both the Kukpowruk and Corwin Formations represent, at least in part, deltaic and near shore facies deposition. In order to justify the assumption that secular variation will average out we must prove that the geological section sampled represents a time interval on the order of at least several tens of thousands of years. If the sampled interval is on the order of 2000 meters thick then the rate of deposition must be 2 cm/yr or less in order that the secular variation field be swamped by the axial dipole field. In many recent deltaic systems this limit is easily exceeded (Reading, 1978) so that it is not clear that the requirements for removing the effects of secular variation have been adequately met. Of course sedimentation in a deltaic system is not continuous and one can make the case that the rock record contains many time gaps and local unconformities, thus the time represented by the sampled section far exceeds 10^5 years. Plant megafossil correlations (Smiley, 1969b) indicate the sampled section stretches from middle Albian to Cenomanian time (approximately 5 million years) however, and this correlation indicates that there is some evidence that the sampled interval is at least several million years long, albeit discontinuous. The question of the length of time represented by the sampling seems fairly well settled by the plant megafossils. The Nanushuk Group spans at least several million years discontinuously, meeting the time requirement to remove secular variation.

Because it is impossible to measure the entire remanent magnetization of the Nanushuk Group rocks en masse, many smaller samples were taken and analysed individually. By measuring the magnetization of the individual samples we hoped to estimate the mean alignment of the entire population of magnetic carriers present in the Nanushuk rocks. Commonly the remanent magnetization is given not in terms of x, y, and z but rather as Inclination, Declination and Intensity. The transformation from coordinates of I, D, R to x, y, z is:

$$x = R \cos I \cos D$$
$$y = R \cos I \sin D$$
$$z = R \sin I$$

The maximum likelihood estimator of the population mean vector given n samples $v_i = x_i, y_i, z_i$ is $v = x, y, z$ where:

$$R^2 = (\sum_{i=1}^{N} x_i)^2 + (\sum_{i=1}^{N} y_i)^2 + (\sum_{i=1}^{N} z_i)^2$$

$$x = 1/R \sum_{i=1}^{N} x_i \qquad y = 1/R \sum_{i=1}^{N} y_i \qquad z = 1/R \sum_{i=1}^{N} z_i$$

It was for the analysis of paleomagnetic data that Sir Ronald Fisher in 1953 published the first statistical analysis of directional data. Fisher (1953) specifically developed statistics for analysis of spherical Gaussian distributions. One limitation of Fisher statistics is that very few directional data samples are spherically Gaussian, therefore some of the Fisher dispersion statistics might not always be consistent gauges of the dispersion of the data. The Fisher statistics k and α used in this study are given by:

$$k = \frac{N - 1}{N - R}$$

$$\cos \alpha_{95} = 1 - (N\text{-}R)/R \left\{ (1/P)^{1/N-1} - 1 \right\}$$

Where N is the number of vectors, R is the resultant length of the vector sum of the sample vectors, and P is the probability that the population mean falls ouside a cone of radius α around the sample mean.

Criteria for Reliability

The conclusion that the remanent magnetism of a rock is a valid indication of the axial dipole field is a subject that has been discussed by many authors. Several criteria have been suggested so that erroneous vectors be eliminated from a paleomagnetic study (Irving, 1964; McElhinney, 1973; Stone et al., 1982). Stable yet undesirable vectors such as could occur through collecting and measuring errors, remagnetization due to lightning strikes, and sampling the geomagnetic field during an extreme excursion should not be included in the statistical analysis because those vectors' directions are not a true indication of the geomagnetic field.

Site means were calculated before any specimens were rejected to determine a preliminary estimate of the mean. The angle Theta$_p$ was then calculated by the method of McFadden (1980).

$$\cos \theta_p = 1 - (N-R) \{ (1/p)^{1/N-1} - 1 \}$$

Theta$_p$ is the best estimate of the angle which will be exceeded with a probability p from a Gaussian spherical distribution based upon a sample of size N with a resultant of magnitude R. Using p = .05 a circle of radius Theta was drawn about the estimate of the site mean and those vectors at an angle greater than Theta from the site mean were rejected. This method risks excluding 5 percent of the good data from the analysis but minimizes the effect of erroneous data points. The selected data (see Tables B1 through B13 in Appendix B) were then used to recalculate a better estimate of the site mean. In the cases for which Theta was undefined for a given N, R, and p a value of 50 degrees was arbitrarily assigned (Stone et al., 1982).

The resultant site means were then evaluated to determine their stability and reliability. First the criteria of McElhinney (1973) was followed in rejecting sites with fewer than seven remaining reliable specimens. This eliminated WNS-01, WNS-04, WNS-05, and WNS-08. The remaining sites were then evaluated to determine if the sample vectors differed significantly from a random (uniform) distribution. The statistical test employed was that of Watson (1956). For value of N a specific k cutoff was calculated for .05 and .01 significance. None of the remaining sites were significantly dispersed and thus rejected by this test (Table 3).

Finally it was determined whether the vector dispersion was greater in the geographic frame of reference or the stratigraphic frame. According to McFadden (1980) for the null hypothesis, H_0: $Kappa_1 = Kappa_2$, (where $Kappa_1$ and $Kappa_2$ are Fisher's precision parameters in the geographic and stratigraphic frames respectively) the relevant statistic is:

$$k_2/k_1 = F(2(N-1);\ 2(N-1))$$

where F(a;b) is a random variable F-distributed with a and b degrees of freedom respectively. If the ratio exceeds the upper significance point in Table 4 then the null hypothesis is rejected and it is concluded that $Kappa_2 > Kappa_1$, with the appropriate degree of certainty and that the improvement of k in the stratigraphic frame is significant. Likewise if $k_2/k_1 < 1.0$ we can conclude that the reduction in dispersion

Table 3

Significance points of k

$$k = \frac{N-1}{N-R}$$

N	0.05	0.01
5	2.67	4.08
6	2.33	3.29
7	2.13	2.84
8	1.99	2.55
9	1.89	2.36
10	1.81	2.22
11	1.75	2.11
12	1.70	2.02
13	1.66	1.95
14	1.62	1.89
15	1.59	1.83
16	1.56	1.79
17	1.54	1.75
18	1.52	1.71
19	1.50	1.69
20	1.48	1.66

H_0: The vectors are randomly distributed.

If calculated vale for k is greater than table value reject null hypothesis at .05 or .01 significance level.

Table calculated from Watson, 1956.

Table 4

Fold Test Statistics

Site #	2(N-1)	k2/k1	If k2/k1 falls within range then k2 and k1 are indistinguishable at the indicated significance level. Significance Ranges .90	.95	Pass ? Fail Status
WNS-02	24	0.78	.59-1.70	.51-1.98	?
WNS-03	14	1.21	.50-2.02	.40-2.51	?
WNS-06	14	1.23	.50-2.02	.40-2.51	?
WNS-07	18	0.39	.54-1.85	.46-2.17	Fail
WNS-09	20	0.79	.56-1.79	.47-2.12	?
WNS-10	12	1.61	.47-2.15	.37-2.69	?
WNS-11	30	0.85	.62-1.61	.54-1.84	?
WNS-12	40	2.66	.66-1.51	.59-1.69	Pass
WNS-13	26	1.19	.60-1.66	.51-1.93	?

of the data in the geographic frame is significant if the ratio of k_2/k_1 is less than the lower significance point. If the value of k_2/k_1 is within the upper and lower significance points then we cannot conclude at the appropriate confidence level that the dispersions in the two reference frames are significantly different. At the 90 percent significance level only site WNS-12 passes this stability test. However, as McFadden and Jones (1981) point out the fold test is a useful test of the stability of magnetic remnance only if the section is highly folded. Furthermore, random errors in measuring the bedding orientation used for correcting the samples to ancient horizontal add a bit of variance to data in the stratigraphic frame which might more than balance the reduced dispersion due to correcting for bedding orientation. For this reason it was decided to reject only those sites for which k_2 was significantly greater than k_1. For only one site, WNS-07, was the dispersion in the stratigraphic frame significantly greater than the dispersion in the geographic frame, thus only WNS-07 was rejected on dispersion criteria. Further implications of the fold test are included in the next section. A summary of the status and magnetic directions of all 13 sites is shown in Table 5.

Fold Test Statistics

The stability of the remaining cores was tested to determine the "stability" of the remnance: Was the post-cleaning remnance truly a stable DRM or rather a later TRM or even a hard VRM? Probably the

Table 5

Summary of WNS Magnetic Directions after thermal demagnetization

Site #	N	Geographic			Stratigraphic			Status
		Dec,	Inc,	(k, a_{95})	Dec,	Inc,	(k, a_{95})	
WNS-01	2	150.8,	57.7,	(9.3,32.4)	145.4,	44.7,	(1.8,73.4)	Rejected N<7
WNS-02	13	184.3,	68.4,	(11.4,11.5)	001.2,	72.4,	(8.9,13.0)	Selected
WNS-03	8	354.3,	86.1,	(4.3,23.7)	332.4,	58.3,	(5.2,21.8)	Selected
WNS-04	3	147.5,	68.8,	(70.6, 9.6)	160.0,	-21.7,	(263., 5.0)	Rejected N<7
WNS-05	1	333.0,	68.0,	(----, ---)	176.0,	68.0,	(----, ---)	Rejected N<7
WNS-06	8	000.1,	50.6,	(41.0, 7.7)	212.2,	69.7,	(50.4, 7.0)	Selected
WNS-07	10	019.8,	67.3,	(35.0, 7.9)	198.1,	70.1,	(13.8,11.9)	Rejected $k_2<k_1$
WNS-08	2	235.8,	68.7,	(3.5,52.9)	248.6,	23.3,	(3.2,55.2)	Rejected N<7
WNS-09	11	040.2,	77.0,	(31.7, 7.5)	232.0,	83.8,	(25.1, 8.4)	Selected
WNS-10	7	226.7,	82.6,	(58.1, 6.9)	245.2,	85.0,	(93.8, 5.5)	Selected
WNS-11	16	139.4,	66.3,	(36.5, 5.8)	268.5,	86.4,	(30.9, 6.3)	Selected
WNS-12	21	181.7,	52.7,	(5.6,12.9)	350.2,	80.5,	(14.9, 7.9)	Selected
WNS-13	14	317.2,	86.3,	(33.8, 6.4)	319.3,	74.5,	(40.3, 5.9)	Selected
Grand Mean	98	163.5,	81.1,	(6.7, 5.5)	318.0,	82.1,	(12.9, 3.9)	

most definitive test of this question is the fold-test (Graham, 1949; Irving, 1964; McElhinney, 1973; McFadden and Jones, 1981). Comparison of the dispersion of the sample magnetizations in the geographic frame of reference with their dispersion in the stratigraphic frame (Figure 15) should enable us to determine the relative ages of the folding and the magnetism. If there have been post-magnetization differential rotations between samples of rocks of the same age the dispersion of the vectors should be greater in the geographic frame (their present orientation) than in the stratigraphic frame (their orientation at the time they acquired their primary remnance). Statistically, the improvement or deterioration of the dispersion can be evaluated with the use of an F-test (McElhinney, 1973). Using such a test on the data from WNS-12 we can accept the hypothesis that the dispersion decreases in the stratigraphic frame with a confidence of better than 99 percent. McFadden and Jones (1981) have proposed a more generalized form of the same test for the case where bedding from 3 "limbs" of a folded rock sequence are known. The McFadden test also confirms the hypothesis that the dispersion decreases in the stratigraphic frame with greater than 99 percent confidence.

The reduction in scatter demonstrated in the fold test can best be understood by examining the sterographic projection (Figure 16) of the magnetic vector directions (Table 6) in the geographic (squares) and in the stratigraphic (triangles) frames of reference. Note that site WNS-12 has been divided into three groupings depending on the

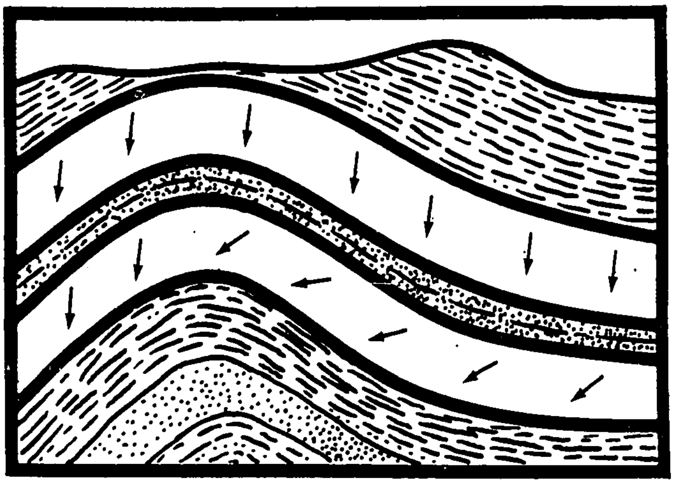


Figure 15. Schematic representation of the fold test. The arrows indicate the remnant magnetization vector of the rock. The upper bed fails the fold test, the lower bed passes the test.

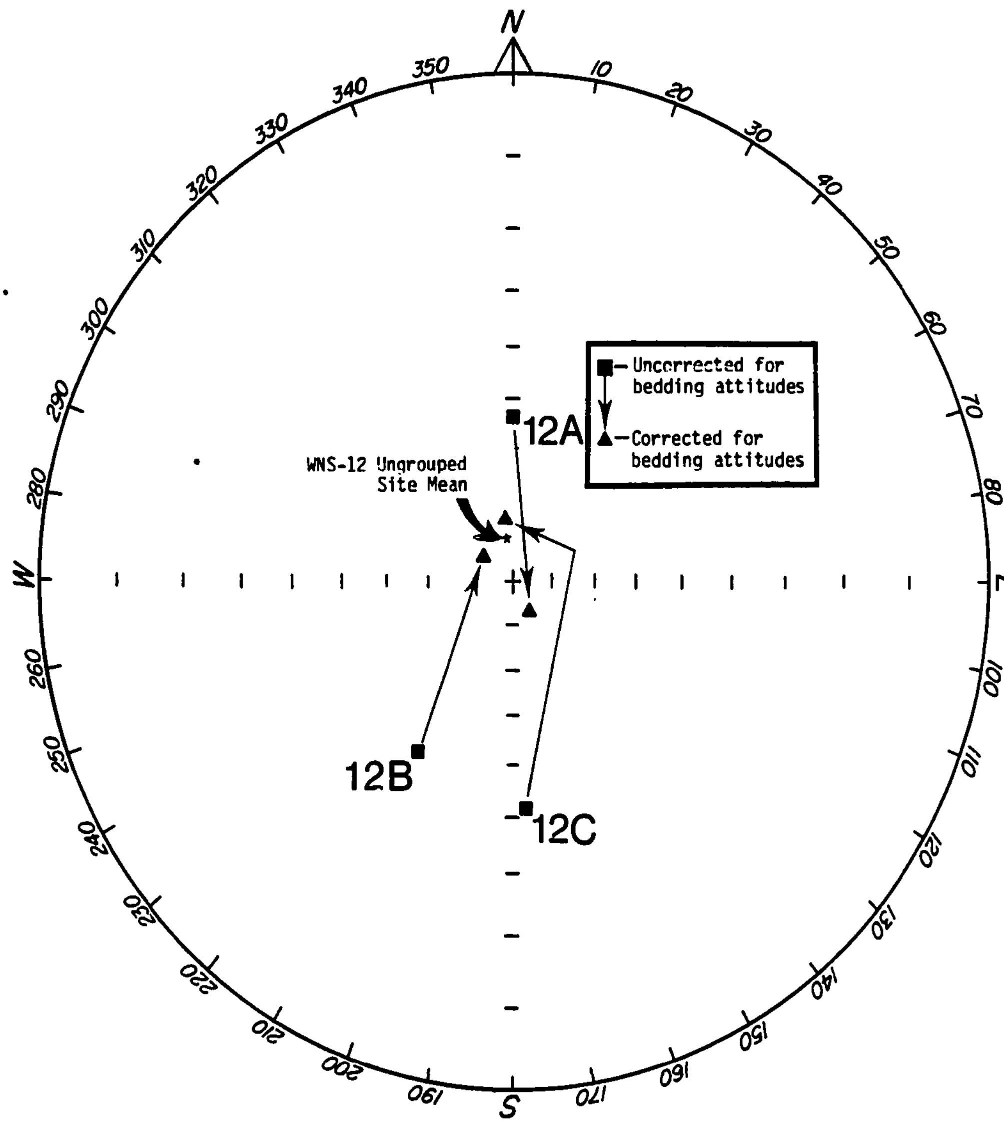


Figure 16. Classic fold test showing a convergence of vector directions of samples from site WNS-12 when bedding corrections are applied. This test demonstrates the remnant magnetization antecedes folding at the 99% confidence level (F-ratio test after the method of McElhinney (1964)). 12A, 12B, and 12C are groupings of the WNS-12 data according to position relative to the fold axis.

Table 6

Cretaceous Nanushuk Group Fold Test

Data from WNS-12

Group	N	Geographic (Dec, Inc, (κ , α_{95})	Stratigraphic (Dec, Inc, (κ , α_{95})
12A		000.7, 54.2, (18.6, 18.7)	147.8, 82.1, (18.3, 18.9)
12B	3	210.5, 47.3, (81.4, 9.0)	306.9, 80.9, (85.6, 8.7)
12C	15	176.3, 41.5, (14.8, 9.4)	353.2, 76.5, (13.7, 9.8)
Ungrouped WNS-12	21	181.7, 52.7, (5.6, 12.9)	350.2, 80.5, (14.9, 7.9)

Paleolatitude estimate = 86.8 (α_{95} high estimate)
71.5 (best estimate)
57.9 (α_{95} low estimate)

structural proximity of the samples with respect to the fold axes. The 12a samples are from the south limb of the Snowbank Anticline while the 12b and 12c samples are from the north limb of the Snowbank Anticline and south limb of the Barbara Syncline respectively (Figure 17).

This result is difficult to interpret unless we have a clear estimate of the timing for the folding. The wide gentle synclines and sharper apex-faulted anticlines into which the Nanushuk sediments have been folded are considered to be the result of the Brookian Orogeny. Folding was probably initiated sometime in the Late Cretaceous. In the region of the Umiat test well number 1 local erosional unconformity within the Nanushuk Group indicates the structural deformation that produced the Umiat Anticline was probably syndepositional (Payne et al., 1952), however Mull (1979) cites an Early Tertiary or latest Cretaceous age for the onset of folding. Although folding continued well into the Tertiary (the youngest beds folded are Tertiary age), the important time is that of the onset of folding. If folding began in the Late Cretaceous, coinciding to or closely following deposition, then the fold test indicates magnetic stability since at least that time.

Preliminary Interpretations

The fold test statistics indicate the magnetization pre-dates the folding and hence is approximately contemporaneous with deposition, i.e., Albian to Cenomanian. Figure 18 shows a stereographic projection of the magnetic vectors from sites WNS-02, WNS-03, WNS-06, WNS-09, WNS-10, WNS-11, WNS-12, WNS-13 in the stratigraphic frame of reference.

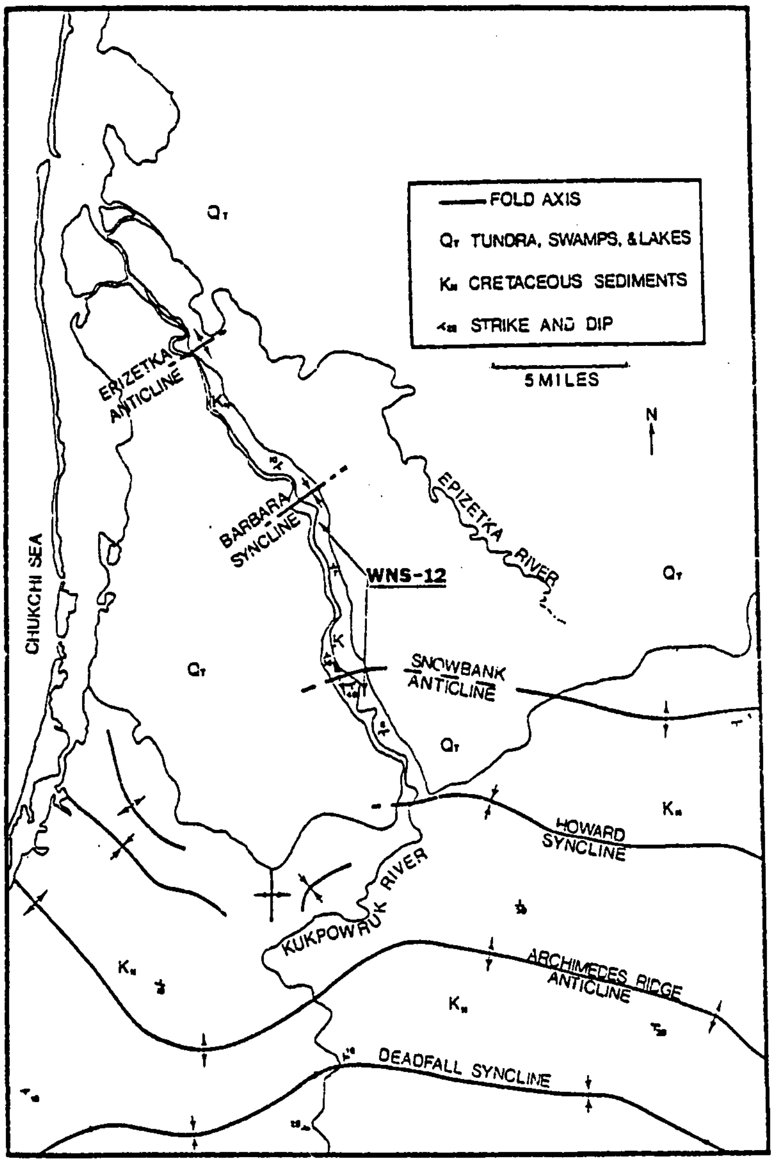


Figure 17. Relationship of WNS-12 sample locations to the Barbara Syncline and Snowbank Anticline.

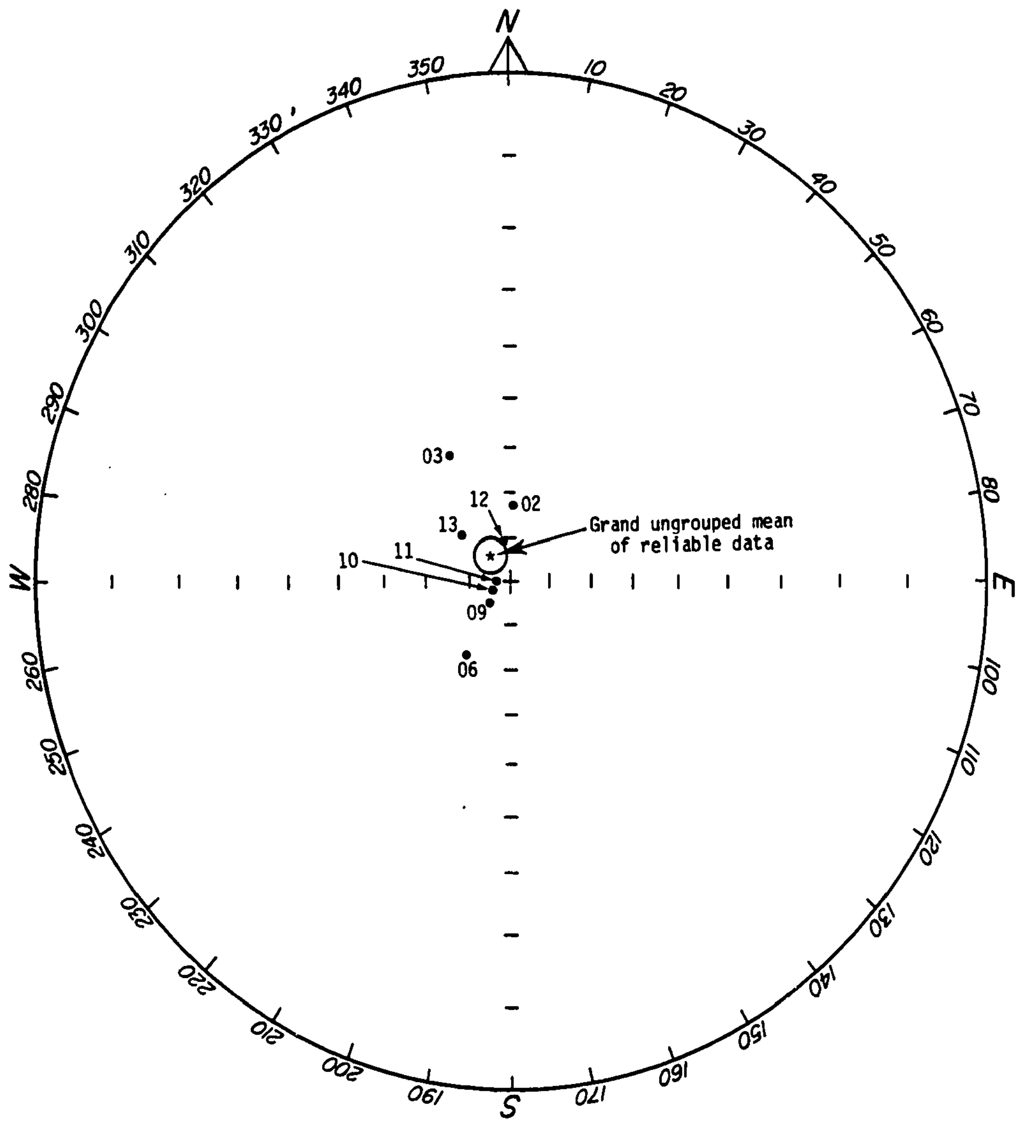


Figure 18. Stereographic projection of the site means of the eight sites determined to be reliable. The asterisk represents the grand mean of the ungrouped reliable data.

Also calculated and plotted is the grand mean of the ungrouped data. From these data a virtual geomagnetic pole (VGP) was calculated and plotted in Figure 19 on a sterographic projection of the northern hemisphere. Also plotted on this figure is the VGP determined from cratonic North America by Mankinen (1978). In order to bring the two together a 100 degree clockwise rotation and about a 20 degree southward shift in paleolatitude is necessary. The paleolatitudinal estimate is considered more dependable however, and the rotation is not wholly proven until we can prove the structural deformation in the area was a single simple event, otherwise considerable declination errors are possible (Figure 20), (Stone et al., 1982).

Figure 21 is a stereographic projection of the northern Arctic region with the major continental blocks of North America and Europe rotated into their relative positions at 105 million years before present (reconstruction according to Pitman and Talwani, 1972). Circles of latitude were drawn about the Eurasian and North American VGP while the lines of longitude were arbitrarily positioned. Present coastlines are used to aid in orienting the reader. Dashed lines indicate the paleolatitude mean obtained from WNS-02, WNS-03, WNS-06, WNS-09, WNS-10, WNS-11, WNS-12, WNS-13 data and the a_{95} confidence interval of that estimate.

The paleomagnetic data seem to indicate that northern Alaska was not in its present position relative to the rest of North America by early Late Cretaceous. This conclusion is at odds with many of the proposed models for the evolution of the Canada Basin and northern

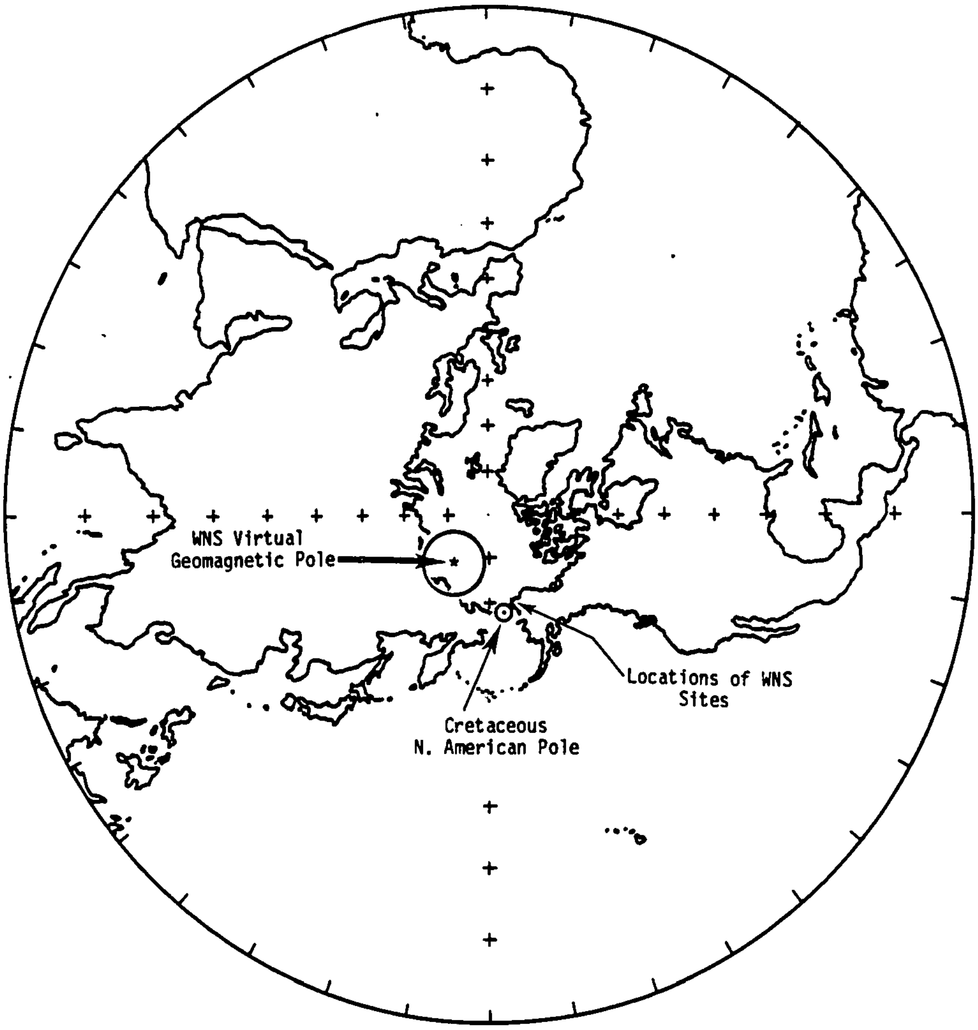


Figure 19. Virtual Geomagnetic Pole (VGP) from the Late Cretaceous Nanushuk Group shown with respect to the present location of the sites and present coastlines. The Late Cretaceous N. American pole position shown was derived from cratonic N. American paleomagnetic data by Mankinen (1978).

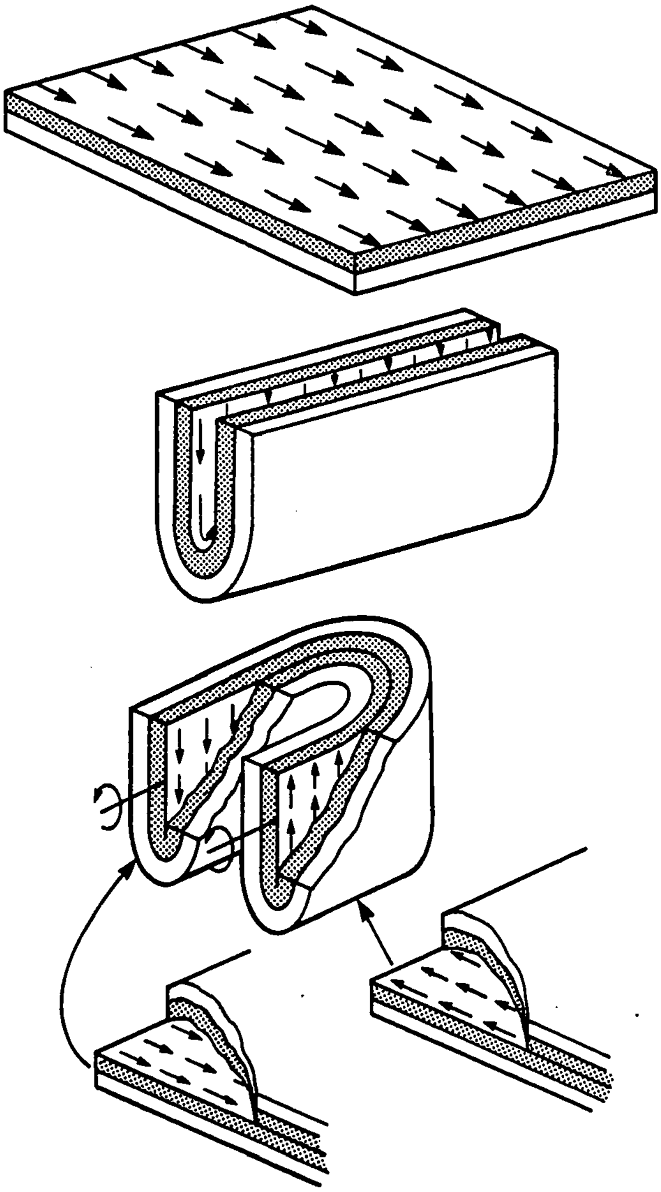


Figure 20. 180° declination error produced as a result of misinterpretation of two episodes of folding as one single episode. The arrows represent the direction of magnetization of the bed. From Stone et al., 1982.

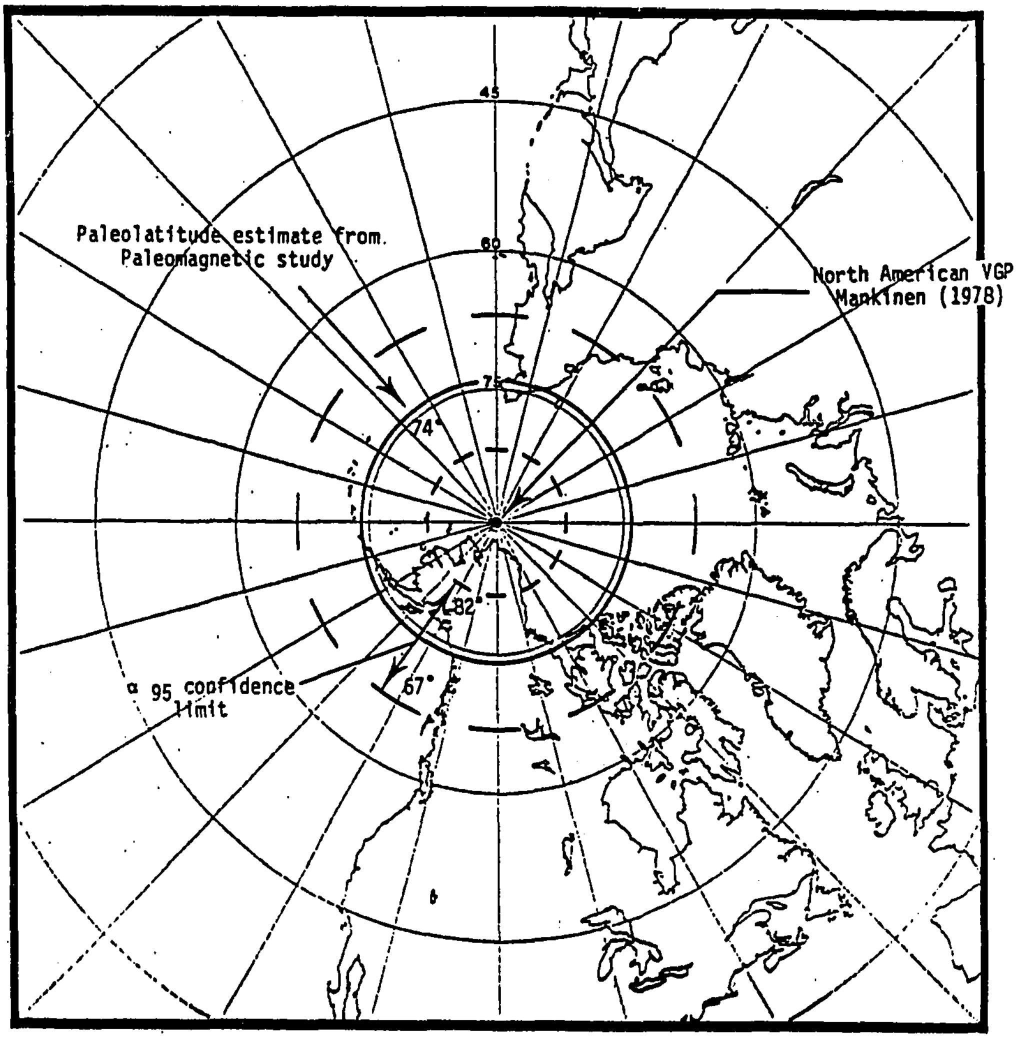


Figure. 21. Plate tectonic reconstruction of major continental blocks showing their positions at approximately 105 mybp. Present coastlines are shown to aid in orienting the reader. Also shown is the paleolatitude estimate with its α_{95} confidence limits. The North American VGP is that of Mankinen (1978).

Alaska. Most of those models (Tailleur, 1973; Newmann et al., 1977; Churkin and Trexler, 1980; Jones, 1980) argue that northern Alaska was in its present position relative to North America by at least the earliest Cretaceous. This 40 million year timing disparity is no small matter and the relative merits of the different reconstructions are discussed in detail in a later section. For now it is sufficient to note that while proving neither the rotational hypothesis nor the northward drift hypotheses the paleomagnetic data seem to be more compatible with the northward drift models because they allow the onset of the Brookian Orogeny to occur in more southerly paleolatitudes.

PALEOBOTANY AND PALEOCLIMATOLOGY OF NORTHERN ALASKA

The Relation Between Paleoclimatology and Paleogeography

Extensive sequences of coal are present in the Cretaceous Nanushuk Group of northern Alaska. Coal resource estimates for Northern Alaska range from 100 billion tons to 4 trillion tons (Tailleur and Brosge, 1975; Barnes, 1967) (Figure 22 and Table 7) which put these coal deposits among the largest coal deposits of North America. These occurrences seen anomalous when one considers that accepted North American paleogeographic reconstructions for the Cretaceous and Cretaceous paleomagnetic data for cratonic North America (Irving, 1979) put northwestern Alaska closer than 10 degrees to the North geographic pole (Figure 19). This raises the question as to whether it is possible for these northern Alaskan coals to have been derived from forests growing so close to the magnetic, and by implication, geographic pole. Several models have been proposed in recent years

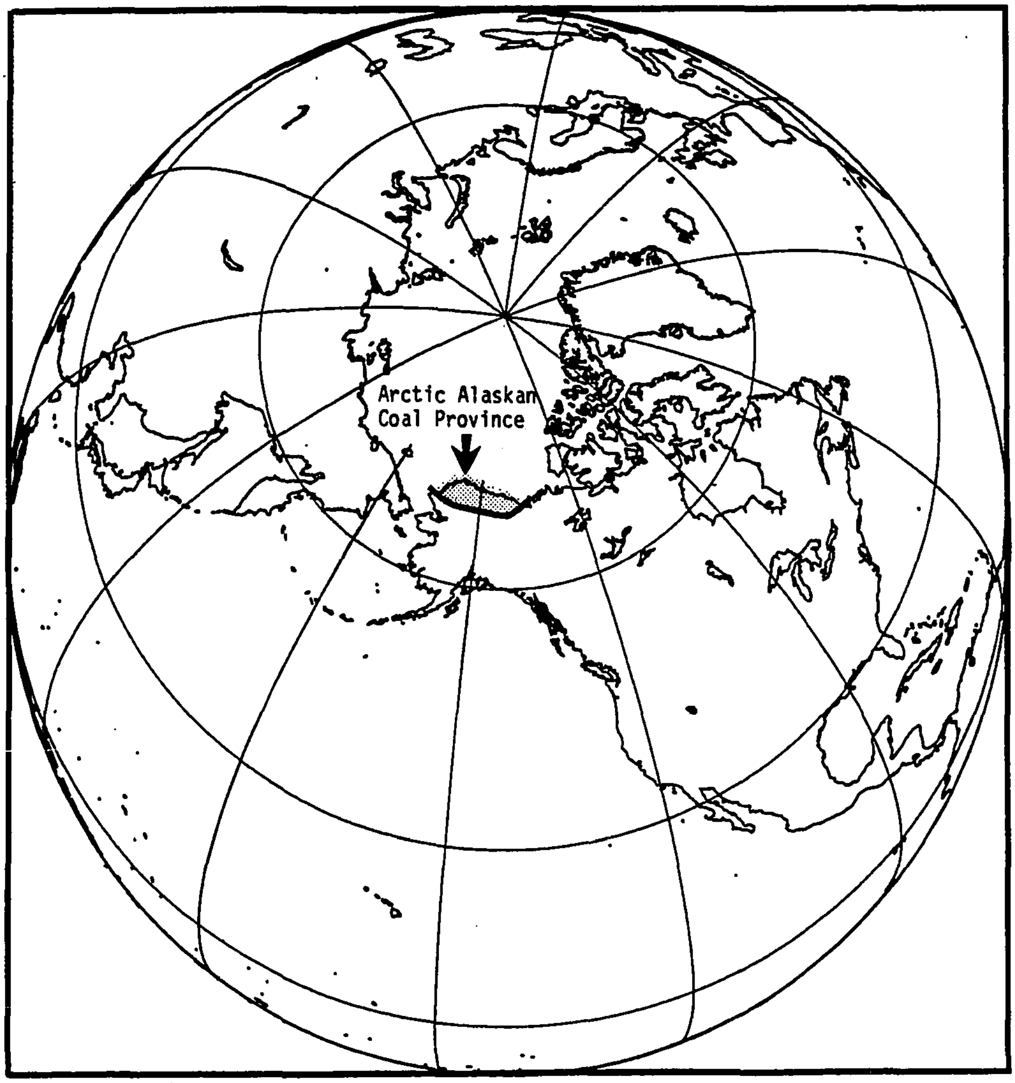


Figure 22. Present location of the Arctic Alaskan Coal Province (stippled). Tailleur and Brosge (1975) estimated coal reserves of between 100 billion and 4 trillion tons for the province.

Table 7

Hypothetical Coal Resources in millions of tons in the Nanushuk Group in the National Petroleum Reserve--Alaska. (from Callahan and Martin, 1980.)

Rank	Thickness (ft)	Subtotals	Total
Sub-bituminous	2.5-5.0 5.0-10.0 10.0+	196,000 215,000 66,900	478,000
Bituminous	1.2-5.0 5.0-10.0 10.0+	170,000 122,000 77,600	370,000
Subtotals	1.2-5.0 5.0-10.0 10.0+	366,000 337,000 145,000	848,000

to explain the evolution of the Canada Basin and northern Alaska (Tailleur, 1973; Newman et al., 1977; Churkin and Trexler, 1980; Jones, 1980). All of these require northern Alaska to be in its present position with respect to North America during Albian to early Cenomanian time. A proper discussion of the relative merits of these models should examine the paleontologic evidence from the Nanushuk Group. Large scale motions of the northern Chukotka-Alaska plate with concommitant reorganization of Arctic paleogeography must in turn have had an effect upon the paleoclimate of the area. The Atlantic Ocean had just begun to open in the Albian (Pitman and Talwani, 1972); and if we assume the continents of Eurasia and North America have had no large scale internal deformations since that time, there must have been a significant oceanic seaway between arctic Alaska and the Siberian Craton. This reentrant, the Sinus Borealis of Dietz and Holden (1970), probably allowed for much more communication with the northern Pacific Ocean than the present Bering Straits. The Bering Sea must have been a significant oceanic seaway with much more communication with the Northern Pacific Ocean. This alone probably excludes the possibility of an Arctic ice cap and results in profound implications for northern Alaska's paleoclimatology.

Previous Paleoclimatic Interpretations of Northslope Floras

Smiley (1967, 1969a) interpreted the paleoclimate of the Late Cretaceous of northernmost Alaska as that of a "humid, coastal plain, near sea level." From an analysis of the latest Early Cretaceous

(Albian) to Late Cretaceous (Cenomanian) Nanushuk and Colville floras and Vakhrameev's (1964) Late Jurassic to Albian sequences in the Kolyma and Lena River areas of eastern Siberia, Smiley decided that the observed paleobotanical distributions were the result of a widely recognized Cretaceous "world-wide" warming (Frakes, 1979). This warming trend peaked during the Albian and was followed by world-wide cooling through the Maestrichian.

Smiley (1976) concluded that the northern and central Alaskan floras as well as the Russian floras from the Lena and Aldan River regions (Figure 23) indicate no relative motion between Alaska and the Chukotsk Peninsula since the Albian. Smiley notes a gradual decline in the similarity of the floral communities as one moves westward with no large jumps along either Churkin's (1972) or Hamilton's (1970) plate boundaries. Smiley (1976) concluded that there have not been any significant tectonic displacements between Eurasia, Siberia, and Chukotka-Alaska and argued that large-scale tectonic movements between the major cratons in the Late Mesozoic are unlikely.

Major plate tectonic motions, as mentioned before, should have profound implications for the paleoclimates of the involved regions. Smiley observed that all paleoclimatic variations could be attributed to world-wide cooling and warming without continental drift or shifts in the inclination of the Earth's axis of rotation. Within the last ten years general acceptance of plate tectonics has grown so that it now represents a major paradigm of geology. Smiley's earlier

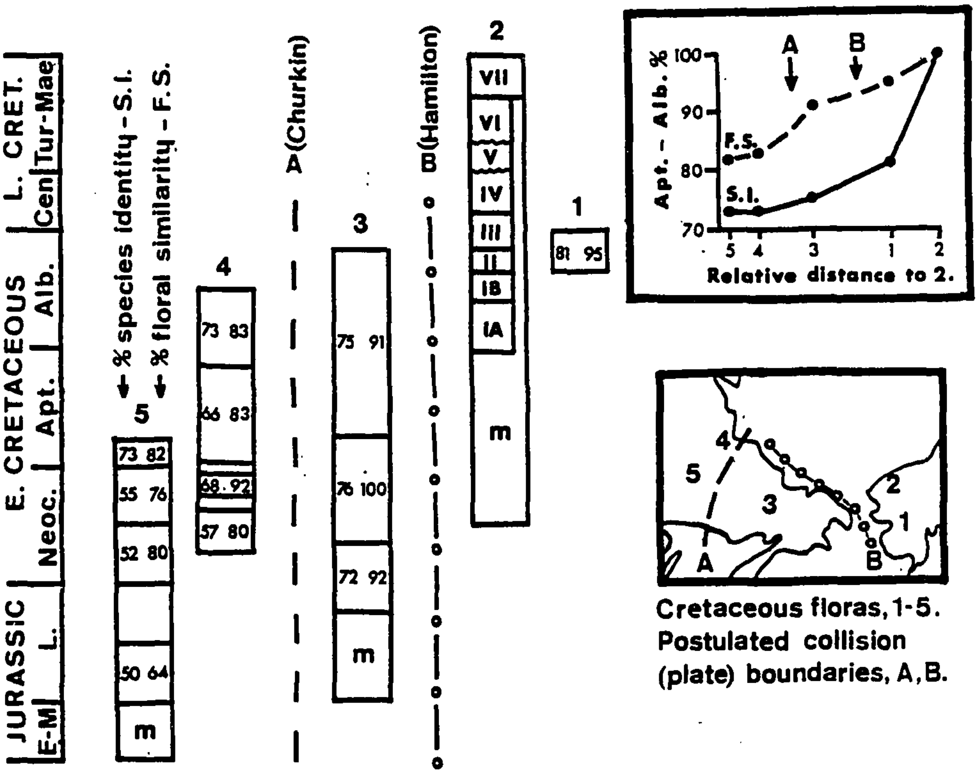


Figure 23. Correlation of five Cretaceous sections across Alaska and Siberia along with graphs of floral similarity and species identity. The species identity index indicates the percentage of species that are identical with ones in northern Alaska. Floral similarity indicates the percentage of species that are identical or closely similar. Marine sections are indicated by a "m". The roman numerals in the location 2 section refers to floral zones of Smiley (1967). According to Smiley (1976) smoothly increasing taxonomic similarity with decreasing distance from northern Alaska precludes the presence of major tectonic dislocations along either the proposed boundaries of Churkin (1972) or Hamilton (1976).

interpretations of Alaskan paleoclimatology should be reconsidered in the light of recent plate tectonic hypotheses.

Even if the Cretaceous was warm enough to permit extensive forests in the polar regions where accepted plate reconstructions would put this part of Alaska at that time (Irving, 1979) (which is 20 degrees farther north than Smiley believed it to be (Figure 21)) plant life in those regions would be subject to extreme seasonal variations in light conditions. Incident light would also be limited to oblique angles placing additional constraints on the amount of photosynthesis possible, thus adding to the problems of producing sufficient biogenic activity to generate a huge coal deposit.

Wolfe (1978) noted that broad-leaved evergreens with medium-sized leaves rarely occur north of 50 degrees latitude today. He hypothesized that the light conditions at latitudes greater than 60 degrees, regardless of the climate, would impose seasonal variations in photoperiod that are too severe for the general survival of broad-leaved evergreens, and that deciduous forms would predominate with perhaps a slight broad-leaved evergreen component.

The role of seasonal variation in light conditions remained primarily an agricultural concept until about twenty years ago. One early article, however, (Allard, 1949) dealt with the significance of photoperiodism on the scale of geological time. Allard suggested that the Cretaceous, which was widely recognized as a period of generally warm and equable world-wide climates during which tropical plant forms extended significantly into the present temperate latitudes, was characterized by near zero obliquity of the Earth's axis. To some extent Allard's hypotheses involve the migration of "geofloras", but a geoflora migration is not necessary to his obliquity argument (Allard, 1948). Allard reasons that Cretaceous floras generally had tropical affinities with tropical forms known from high latitudes in both the northern and southern hemispheres (e.g. Mildenhall, 1976; Frakes, 1979; McKenna, 1980). He argued that these floras had evolved temperature and photoperiod affinities based on an equable climate with an invariable twelve hour day. A gradual departure from near zero obliquity in the early Tertiary brought about two important stresses on the early Tertiary high latitude floras. First, the high latitudes became less equable and second, the annual variation in photoperiod became severe. Angiospermous forms were in their earliest stages at the time of this revolution in photoperiod. Perhaps some of these herbaceous angiosperms were already short-day types or annuals and Allard suggests these types filled the gaps left by the declining gymnospermous types. From this point on Allard relied upon the "dispersal" and migration of what Chaney (1940) called the "Arcto-Tertiary Geoflora". The geoflora concept has given way to more evolutionarily sound hypotheses concerning the relationship between Tertiary floras, but the underlying mechanism for the early Tertiary paleobotanical revolution is the same as other authors have recently proposed, principally Wolfe (1975, 1977, 1978, 1980).

Light and the Physiology of Plants

The role of photoperiodism in plants is related to a unique metabolic mode in plants: Photosynthesis. It is through photosynthesis that plants can capture and store the energy of sunlight. In order to use that energy plants must respire (take in oxygen, give off carbon dioxide). Most plants rely entirely on food produced by their own photosynthesis to maintain their respiration. Both photosynthesis and respiration are complex functions of many environmental factors such as temperature, light, and availability of water and nutrients. Each species has a characteristic relationship between these variables. The point where photosynthesis just balances respiration is termed the compensation point. The compensation point is an indication of the minimum light level that the plant can survive indefinitely. Light levels below the compensation point represent a net loss of food for the plant and under these conditions the plant would eventually starve. The light compensation points for various groups of plants are shown in Table 8. In Table 9 the average daily insolation in Fairbanks for each month is presented (Wendler, 1980). Throughout this analysis Fairbanks (65 degrees of latitude) insolation is assumed to approximate the insolation in northern Alaska during Albian to early Cenomanian time, assuming no changes in the obliquity of the earth's spin axis (67-82 degrees paleolatitude as determined by the paleomagnetism study). Table 8 also shows the equivalent light intensity if each day's insolation were spread over twenty-four hours. These simple calculations, based on observed solar radiation, point out the

Table 8

Compensation points of various plant groups in watt/m^2. Data from Larcher (1973).

Plant Group	Compensation Point (watt/m^2)
Herbaceous plants	
C_4 plants	1.47-4.41
Crop plants (C_3)	1.47-2.94
Sun plants	1.47-2.94
Shade plants	0.29-0.74
Deciduous trees	
Sun leaves	1.47-2.21
Shade leaves	0.44-0.88
Evergreen trees	
Sun leaves	0.74-2.21
Shade leaves	0.59-0.44
Mosses	0.59-2.94

Table 9

Solar radiation in Fairbanks (latitude = 65°N)
From Wendler, 1980.

Month	Mean of the daily solar radiation watt/m^2	Equivalent radiation in 24 hrs. of constant light watt/m^2
January	127.9	5.33
February	748.3	31.18
March	2324.6	96.86
April	3876.0	161.50
May	5517.2	229.88
June	5103.5	212.65
July	4941.3	205.89
August	3762.0	156.75
September	2248.8	93.70
October	801.6	33.40
November	185.4	7.73
December	42.1	1.75

extreme efficiency of plants at low light levels. Only in the month of December would a few plant groups not "break even". This analysis ignores the manner in which light is distributed throughout the day. December certainly does not consist of days of uniformly low light level (1.75 watt/m^2). Perhaps the maximum light levels during December days are too great to be effectively used by the plant. Plants have a saturation point at which further increase in illumination produces little or no further increase in rate of photosynthesis. Figure 24 graphically shows this relation for shade and sun leaves of two trees. If a significant portion of the daily insolation were received at intensities greater than the saturation point this radiation could not be effectively used by the plant. Table 10 shows typical saturation points for some major plant groups.

These data are to be compared to the mean diurnal course of solar radiation in the representative months shown in Figure 25. For only three groups (the shade components of herbaceous, deciduous, and evergreen plants) is saturation approached if the maximum light intensity at noon in December is approximately 20 watt/m^2. These, however, are the groups with the lowest compensation points (Table 8). Thus all of the representative plant groups in Tables 8 and 10 would barely survive the light regime in Fairbanks.

Surviving and thriving are two quite different things. Even if a plant survived the Fairbanks light regime it does not follow that these plants would reproduce in Fairbanks. Indeed it is the functions of reproduction that are most drastically affected by a photoperiod

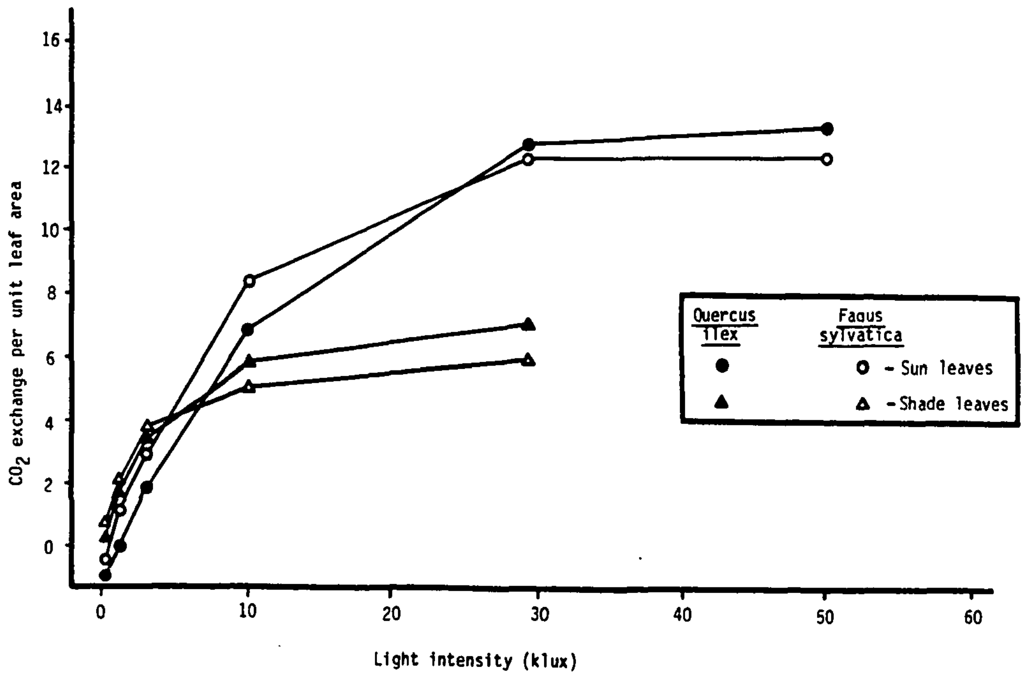


Figure 24. Light response of sun and shade leaves of Quercus ilex (sclerophyllous) and Fagus sylvatica (deciduous) illustrating light saturation. From Larcher, 1969.

Table 10

Saturation points of various plant groups.
From Larcher (1973)

Plant Group	Saturation Point (watt/m^2)
Herbaceous plants	
C_4 plants	117.6+
Crop plants (C_3)	44.12-117.6
Sun plants	73.53-117.6
Shade plants	7.35-14.71
Deciduous trees	
Sun leaves	36.76-73.53
Shade leaves	14.71-22.06
Evergreen trees	
Sun leaves	29.41-73.53
Shade leaves	7.35-14.71
Mosses	14.71-29.41

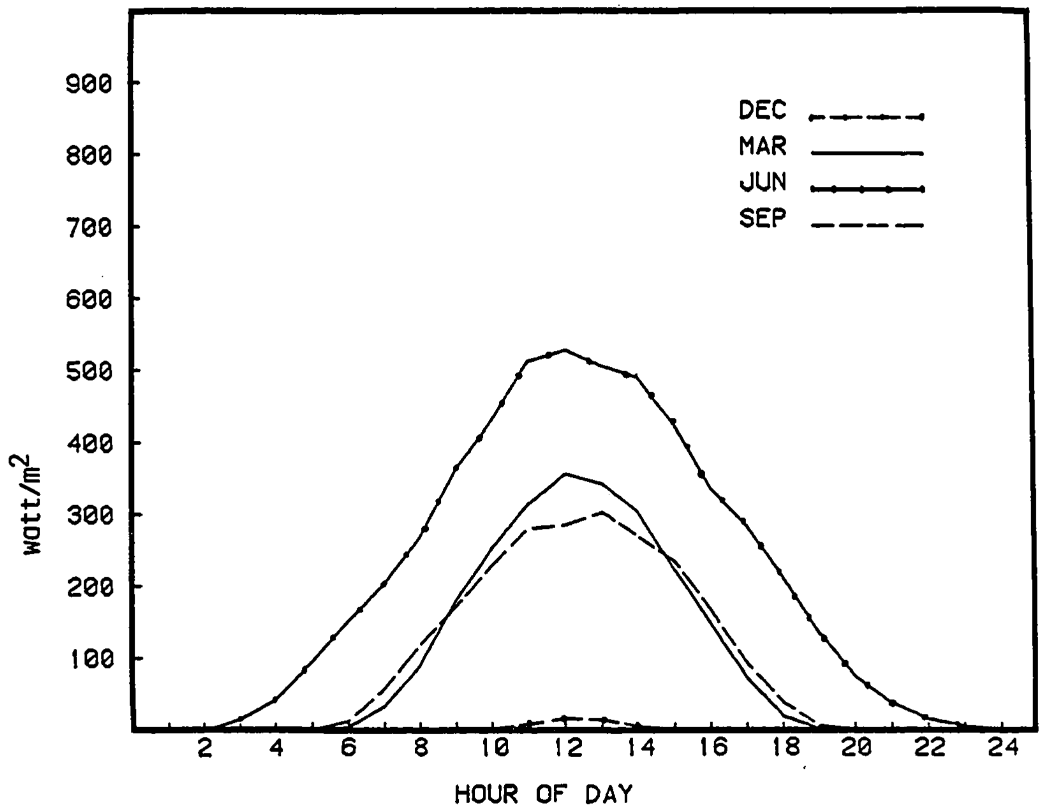


Figure 25. Mean diurnal course of solar radiation in Fairbanks (Latitude = 65°) in December, March, June, and September. From Wendler, 1980.

stress. Failure to flower or set seed could be just as fatal to the long-term survival of a plant species in a specific area as starvation.

The most we can conclude from Larcher's data is that the light regime in Fairbanks today is just barely sufficient for the survival of evergreens. Presumably herbaceous (annuals or perennials) and deciduous forms could cope with this light regime by entering a dormant state for whatever period was necessary. The survival of broad-leaved evergreens at latitudes greater than 65 degrees (Fairbanks) is very doubtful. This constraint on the latitude of evergreen forms is not dependent so much on the adaptation of a single plant as on the limits of photosynthesis.

Sunlight is just one factor in the total environment of the plant. Rainfall, temperature, and nutrients all also add or detract from the possibility of survival of plants. These are not discussed in this paper as they are part of much more complicated systems whose history through geologic time is difficult to interpret. Temperature, a seemingly simple parameter to handle, is complicated by the patterns of oceanic and atmospheric gyres, the output of the sun, and other factors. Even if the problem of nonequable solar radiation is solved (by changes in obliquity or redistributing the land masses) a much more powerful process of heat transfer must be proposed than the present system of oceanic and atmospheric gyres, to allow equatorial heat to be pumped up to arctic latitudes. The wider, and probably deeper, Sinus Borealis might allow such heat transfer. Temperature further complicates the simple analysis of light compensation points by changing both the rate of respiration and photosynthesis. Figure 26 shows the relation between net photosynthesis and temperature compensation for four species. The solid lines indicate the amount of CO_2 used by photosynthesis. The dashed lines indicate the CO_2 derived from respiration. The temperature compensation point is defined as the temperature where the CO_2 derived from respiration equals that consumed by photosynthesis.

Although the complicated variables of rainfall, temperature, and nutrients are all extremely important to plant survival, it seems that none of these environmental factors could ameliorate the sunlight regime to allow for the prolific broadleaf evergreen floras of arctic Alaska in the Cretaceous. On the other hand the effects of changes in other physical properties of the atmosphere, such as optical scattering, should be investigated.

Latitudinal Extent of Broad-Leaved Evergreens

The effect of temperature on respiration and photosynthesis and thus on the compensation point could result in another stress upon the system. If the obliquity of the Earth has remained fixed, the resulting seasonal variation in temperature (corresponding to a variation in light) allows low temperatures in the winter to mitigate the respiration losses when photosynthesis is at its lowest level. If we attempt to allow for tropical forms at high latitudes by simply raising the mean temperature of the entire Earth the resulting warm winters would not allow low winter respiration rates to match the

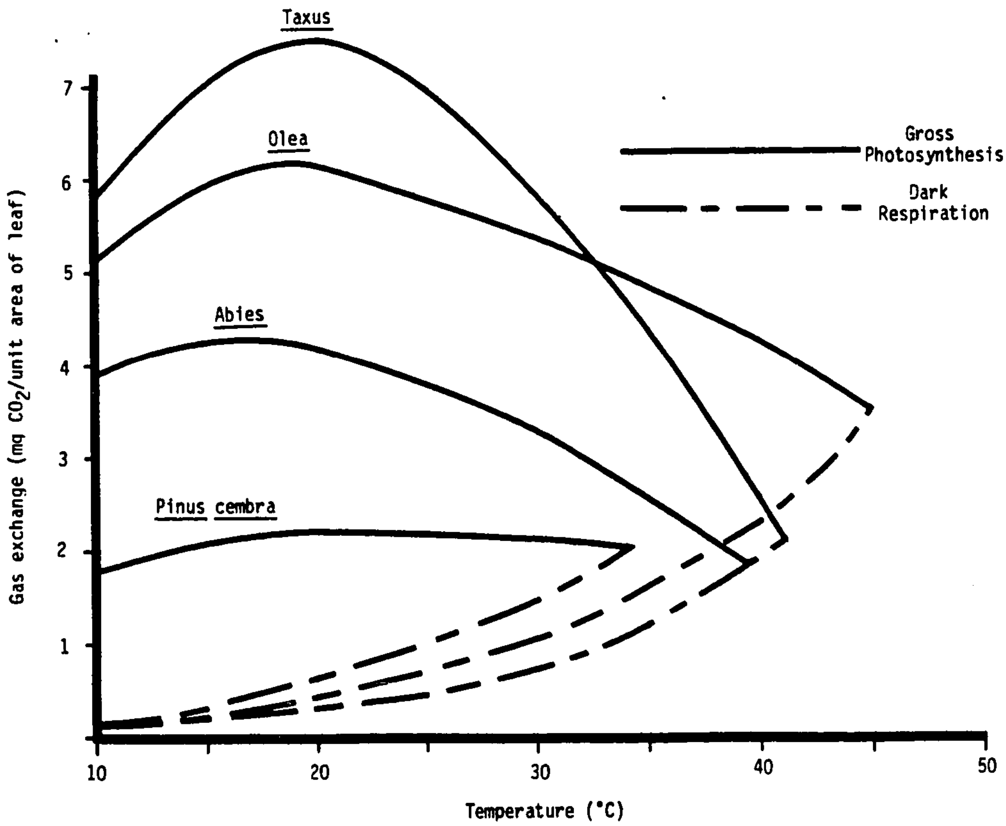


Figure 26. Relationship between gross photosynthesis, dark respiration, and temperature in various species. The intersections of the dashed and solid lines indicate the compensation temperatures, at given light level, for each species. From Bannister, 1979.

low photosynthetic rate. Only a decline in the seasonality of insolation would allow for the survival of broad-leaved evergreen forms. This interpretation is not based upon inferred uniformity through time of any of various plant species, which is a dubious assumption, but rather on an inferred uniformity of the process of photosynthesis. When discussing the limits of photosynthesis one deals with quantities which are far less variable than genetic characteristics; the rate and process of photosynthesis is more akin to a chemical reaction and as such should be less variable in time.

From some general observations concerning the light compensation points of various plant groups, it is possible to establish minimum light intensities for those plant groups. When those minimums are compared with the observed light levels in Fairbanks, we see that daily light level is a limiting factor in mid-winter. Plants unable to enter a winter dormant state would probably not survive the Fairbanks light regime. These interpretations are similar to those made by Wolfe (1978, 1980), although Wolfe's observations were based on plant biogeography.

It would be a simple exercise to extend these observations to include other varieties of plants (perhaps including the exotic Northslope floras of Scott and Smiley, 1979) if compensation point data were available for those exotic types. Further work is needed to determine the limits of photoperiodism for plants other than agricultural varieties, if photoperiodism is to be used in the interpretation of ancient environments. Photoperiodism is, however, a plant characteristic that is not limited in the way that compensation point is. Photoperiodism can be significantly altered by natural selection and as such can not be used in any uniformitarianistic argument.

In the coal bearing deposits of northern Alaska Smiley observed the Albian floral dominants to be "ferns, cycadophytes, dissected ginkgoids and conifers" (Figure 27). Almost all contemporary cycads and conifers have evergreen habits while the only contemporary ginkgoid, Ginkgo biloba is deciduous. The weight of the paleobotanical evidence would seem to be against an extreme polar location for the development of these coals. The sometimes ambiguous relationships between living and extinct plant species leads to a problem inherent in paleontological generalizations. Interpretations of paleoclimates and botanical habit, for instance deciduous vs. evergreen, is prone to error if based solely upon taxonomic and strict evolutionary relationships. Paleoclimatic interpretation should also be based upon the physical aspects of the paleobotanical material. Useful physiognomic characteristics of broad-leaved foliage include: Type of margin, size, texture, type of apex, and the type of base and petiole (Wolfe, 1970, 1979). These physiognomic characters have yet to be fully studied in the Cretaceous floras of the Alaskan Arctic.

In Wolfe's (1978) interpretations of Tertiary floras of western Washington and the Gulf of Alaska, a large gradual decrease in the obliquity (to approximately 5 degrees in the middle Eocene) followed by a rapid increase (to approximately 25 to 30 degrees at the end

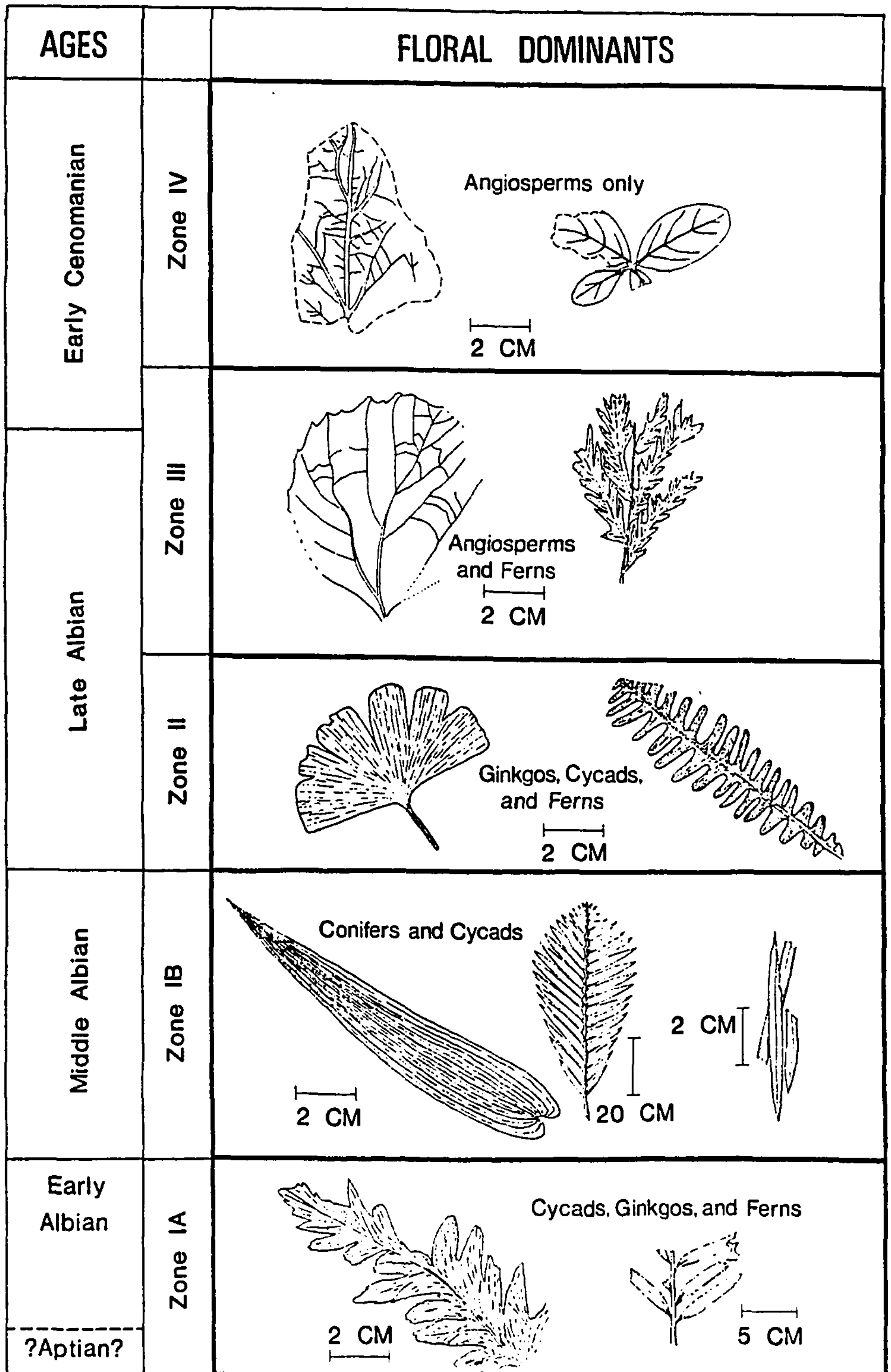


Figure 27. Mid-Cretaceous arctic Alaskan floral dominants.

after Scott and Smiley, 1979

of the Eocene) could possibly account for the Tertiary climatic trends described by Wolfe. Wolfe, much the same as Allard (1948), suggests that the spin axis of the Earth changed in response to precession and astronomical perturbations similar to those hypothesized by Ward (1973). The actual mechanisms that could be responsible for such variations in the inclination of the Earth's axis are necessarily complex and have yet to be adequately explained. Although they could account for some of the observed variations in climate and paleobotanical distributions these variations can also be explained through changes in the regional paleogeography.

Paleobotany of Canadian Arctic Islands

Preliminary palynological interpretations of Albian spores and pollen from Ellef and Amund Ringes Islands and Melville Island of the Canadian Arctic Archipelago indicate a moist, warm-temperature climate (Hopkins, 1971; Hopkins and Balkwill, 1973; Hopkins, 1974). These rocks can be directly tied to the North American craton since at least Paleozoic time (Balkwill, 1978; Kerr, 1980) and based on paleomagnetic data must have been situated at approximately 70 $\pm$ 5 degrees latitude at the beginning of Albian time. The inferred floral assemblages indicate that the sub-arctic climatic regime was considerably warmer than at present. The microflora indicate the predominant forms to be conifers and ferns with a minor component of monocolpate pollen attributed to Cycadales or Bennettitales.

Comparison of microfloras of the Canadian Arctic with the megafloras described by Smiley (Scott and Smiley, 1979) for northern Alaska is at best problematic. The relative differences in taphonomy of spores and pollen versus leaf and stem remains are exceedingly difficult to evaluate and interpret. At first glance it would seem that northern Alaskan floras were richer in broad-leaved evergreen components than the Canadian Arctic Islands floral communities, but paleontological control is not sufficiently fine to allow a meaningful contrast to be drawn. If northern Alaska was in its present position relative to North America in the Albian, as most tectonic reconstructions demand, the Canadian Arctic Island floras (latitude 70 $\pm$ 5 degrees) should show strikingly greater tropical affinities than the northern Alaskan floras (latitude 88 $\pm$ 5 degrees). However the presence of what might be interpreted as broad-leaved evergreen pollen in the Canadian Arctic Islands sample (with paleo-latitude greater than Wolfe's (1980) empirical northern limit for broad-leaved evergreens) is in itself perplexing and casts a small shadow of doubt on the entire analysis. This data from the Canadian Arctic Islands, if substantiated by megafossils collected from this same section, would tend to support the variable obliquity model of Wolfe (1978). This also assumes, reasonably, that the Arctic Islands were tied to North America through all the Mesozoic.

PALEOGEOGRAPHY AND PLATE TECTONICS

Introduction

It has become apparent on the basis of paleomagnetic, structural, and stratigraphic observations that northern Alaska has not remained rigidly fixed with respect to North America throughout the Paleozoic and Mesozoic (Tailleur, 1969, 1973; Newman et al., 1977; Sweeney et al., 1978; Churkin et al., 1979; Mull, 1979; Kerr, 1980).

The Arctic Alaskan or Chukotka-Alaskan plate (Figure 28) as defined by Newman et al. (1977) or Churkin (1973) and Churkin and Trexler (1980) is believed to be bordered on the south by the Kobuk Suture and on the north by a typical passive continental margin. Arctic Alaska's eastern and western margins are less well understood. The eastern margin is probably marked by the Porcupine lineament near the MacKenzie Delta. In the west several boundaries have been suggested (Churkin, 1973; Patton and Tailleur, 1977; Sweeney et al., 1978; Churkin and Trexler, 1980) and include differing amounts of the Chukotsk Peninsula northeast of the southern Anyuy Foldbelt as part of a large "Chukotka-Alaska plate", while Churkin (1973) included the Kolyma Block as part of Chukotka-Alaska.

Rotation Hypothesis

The motion commonly ascribed to the Chukotka-Alaska plate (Rickwood, 1970; Tailleur, 1973; Newman et al., 1977; Grantz et al., 1979) is a counter-clockwise rotation out of the Canada Basin initiated in the latest Jurassic and completed in the Cretaceous. This hypothesis puts the study area in northern Canada in the Early Jurassic with the counter-clockwise rotation ending in about Neocomian time with a continental collision with parts of southern Alaska. This

Figure 28. The arctic Alaskan or Chukotka-Alaska plate as defined by Churkin and Trexler (1980) and its relationship to other tectonic elements of the Arctic Ocean.

reconstruction results in some possible conflicts with the bathymetry (Sweeney et al., 1978) and with the available magnetic anomaly data from the Arctic Ocean (Vogt et al., 1979). The supposed fit between the two segments of continental margin (Figure 29) and also the space available for the rotation are also problematic.

The Chukchi Borderland forms a bathymetric plateau that extends nearly 200 kilometers perpendicularly from a nearly linear continental margin. However, the Chukchi Borderland has no complimentary embayment in the Sverdrup Basin region into which it could possibly fit. Grantz et al., (1979) suggest that the Chukchi Borderland rifted off Chukotka Alaska after rotation thus preserving a linear northern margin for Chukotka Alaska until after rifting. The evidence for this possibility is tenuous and more data from the Chukchi Borderland are needed.

Originally the rotation hypothesis was proposed to help explain the similarity between the Ellesmerian lithologies of northern Alaska (Brosge and Tailleur, 1971; Detterman et al., 1975; Grantz et al., 1979), and the Ellesmerian section in the Sverdrup Basin (Balkwill, 1978), the paleocurrent directions in those rocks, and the paleomagnetic data of Newman et al., (1977). Recently Churkin and Trexler (1980) have noted that paleocurrent data in northern Alaska and the Sverdrup Basin both show east to west transport. Thus a similarity in paleocurrent direction is noted in arctic Alaska and the Sverdrup Basin in their present configuration--with no rotation. Additionally, those clastics, assumedly related to the onset of rifting, are of neither the same provenance nor age. Furthermore, Hillhouse and

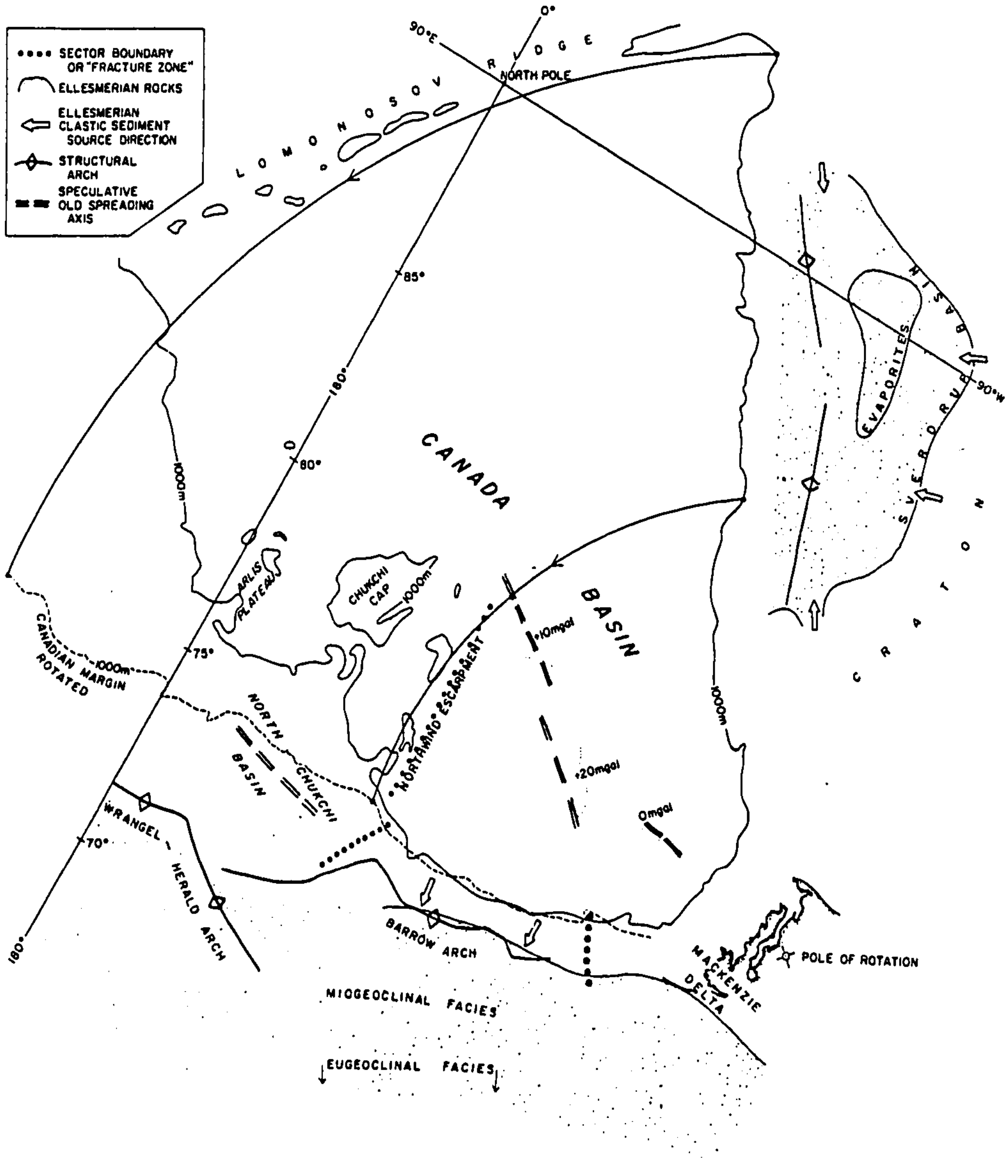


Figure 29. The Canadian arctic continental shelf (as defined by the 1000 M isobath) after rotation about a pole at 69.1°N, 130.5°W. From Grantz et al., 1979.

Gromme (1981) concluded that ". . .the thermal disturbance created by the Brooks Range Orogeny has probably destroyed the Paleozoic magnetic signature that is required to prove the rotation hypothesis."

Other evidence cited (Grantz _et al_., 1979) in support of the rotation hypothesis includes geophysical and geological data such as 1) the bathymetric fit of the Canadian Arctic Archipelago to the northern edge of Chukotka-Alaska if the Chukchi rise is collapsed back into the continental margin and 2) positive free air gravity anomalies which trend across the Canada Basin roughly bisecting the region of "spreading". The gravity anomalies are believed to indicate anomalously shallow crust associated with a spreading ridge; and 3) the roughly correlative Ellesmerian sections of Arctic Alaska and the Sverdrup Basin.

A high degree of correlation between geologic sections of shelf sediments from two passive margins thousands of kilometers apart but adjacent to the same ocean should not be surprising, however. If the two sections were located on relatively stable margins within a reasonable latitudinal range, eustatic sea-level variations could produce very similar geologic sections with parallel depositional histories and even similar biostratigraphies at widely separated locations.

Northward Drift Models

In contrast to the rotation hypothesis, several other hypotheses have been advanced which advocate a northerly motion of

Chukotka-Alaska in the Mesozoic (Jones, 1980; Churkin and Trexler, 1980). Much of southern Alaska and western Canada consists of large blocks and tiny slivers of continental and oceanic crust that have experienced large northerly motions in the past (Jones et al., 1977; Monger and Irving, 1980; Stone et al., 198?). If in fact there is only a little triangle of truly "ancestral" Alaska, (Figure 1) then the possibility of crustal movement into the Arctic Ocean from the Pacific is very good. The accretion of the interior Alaskan terranes had probably begun by the late Early Cretaceous; how far that accretion had progressed is unknown. The Sinus Borealis was probably wider during the Cretaceous for at least two reasons: the closing of the Atlantic and the incomplete accretion of southern and interior Alaska.

Jones (1980) suggests that two major strike-slip systems have dominated the tectonic history of Alaska and the Canada Basin in the late Paleozoic and Mesozoic. The Kaltag fault system (Figure 30) extends northeasterly from near Unakaleet along the Yukon and Porcupine Rivers through northwestern Canada and along the northern edge of the Canadian Arctic Archipelago where it joins the North Atlantic spreading ridge system. The trace of the Kaltag Fault system is approximately a small circle as would be demanded by a transform strike-slip system. Jones recognizes another major strike-slip system, the Tintina Fault system, which extends from its junction with the Kaltag system southward through virtually the entire length of the Yukon. The Tintina system gradually loses its definition in British Columbia as its motion is taken up by the many strike-slip features of the western

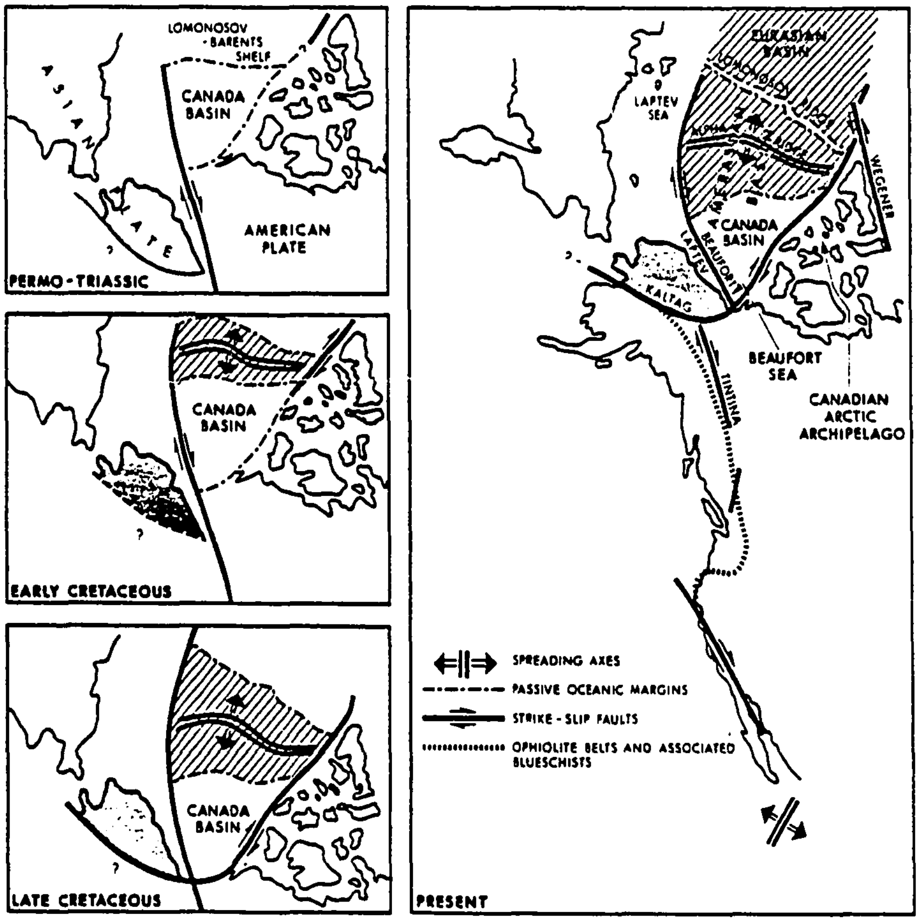


Figure 30. A model for the evolution of the Canada Basin and arctic Alaska proposed by Jones (1980).

North American Cordillera. The northward extension of the Tintina is Jones's hypothetical "Beaufort-Laptev Fault", a strike-slip feature roughly traced by the Alaskan boundary of the Canada Basin (Figure 30). The offset between the Tintina and the Beaufort-Laptev Faults is attributed to dextral slip of about 560 kilometers along the Kaltag Fault. Jones's picture of the tectonic evolution of northwestern North America and the Canada Basin is dominated by the interaction of these two intersecting fault systems. One possible interaction of two roughly perpendicular strike-slip faults is demonstrated in Figure 31. Assuming episodic alternating movement of the two systems, the result is a large number of slivers and blocks arranged in a chaotic manner. Even if the rest of Jones's model is shown to be incorrect with respect to the Arctic, this chaotic jumble of dissected terranes should be kept in mind when speculating about the mechanics of assembling "accreted" terranes.

One troublesome point to consider while evaluating Jones's model is the nature of the Alpha-Mendeleyev Cordillera of the Canada Basin. Jones calls upon spreading about the Alpha Cordillera to absorb the bulk of the northward movement upon the Beaufort-Laptev and Tintina systems. Transform strike-slip faults can only be terminated by spreading ridges or subduction zones. There is evidence, however, that indicates the Alpha ridge is neither an active nor a fossil spreading center. The Alpha ridge lacks almost all the geophysical indications associated with an active spreading ridge such as seismicity (Wetmiller and Forsyth, 1978) and elevated heat flow (Judge and

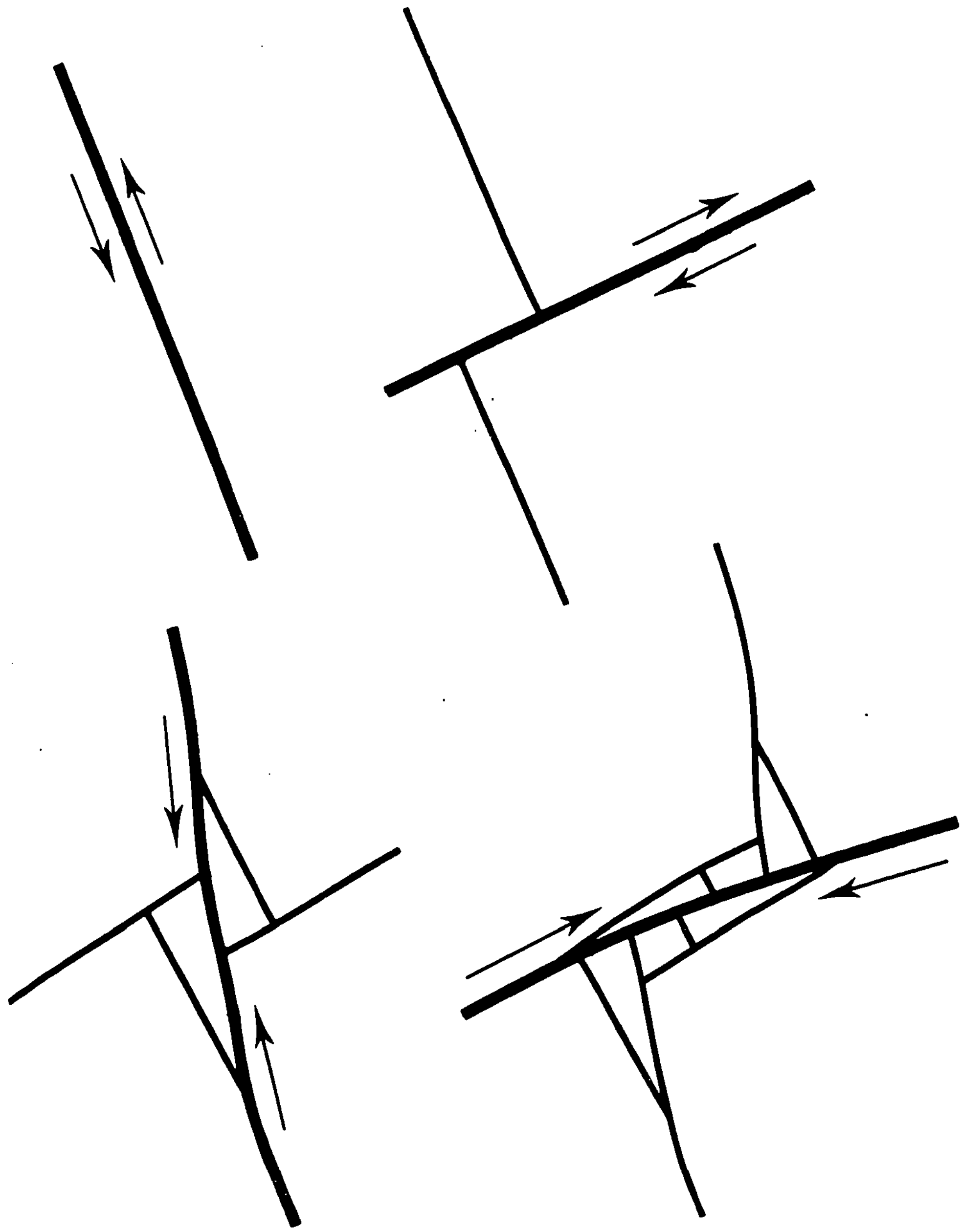


Figure 31. One possible scheme for the interaction of two active strike-slip systems.

Jessop, 1978). Similarly if the Alpha ridge had been an inactive spreading center since the Late Cretaceous, it should have long ago cooled and adjusted isostatically (DeLaurier, 1978). Within 40-70 million years following the end of active spreading the topographic relief of the Alpha Ridge should be less than 500 meters instead of the observed 2900 meters (DeLaurier, 1978; Parsons and Sclater, 1977). Alternative origins for the Alpha Cordillera have been proposed by several authors: A sunken crustal block (King et al., 1966), a transform fault swarm (Hall, 1970; 1973), a subduction or deformation zone (Herron et al., 1974). As an alternative to spreading along the Alpha Cordillera the northward strike-slip of Chukotka Alaska Plate might be somehow absorbed along the East Siberian Canada Basin, a region of severely deformed crustal blocks.

Jones's model does have many attractive points, however. His model acounts for the northerly highlands that supplied detritus for the Paleozoic clastics of northern Alaska--their source, in his model, was somewhere in the central Yukon (Figure 30). The model also supposedly restores a missing section of the Permian shelf deposits of the central Yukon (Jones, 1980) although the details of this restoration are vague. Jones's model also might fit the paleomagnetic and paleobotanical results of this study. Figure 32 shows Chukotka-Alaska in a position relative to North America which is consistent with the paleolatitude indicated by this study. This configuration is somewhat consistent with that proposed by Jones (1980). The main problem is one of timing. Jones does not elaborate on the timing

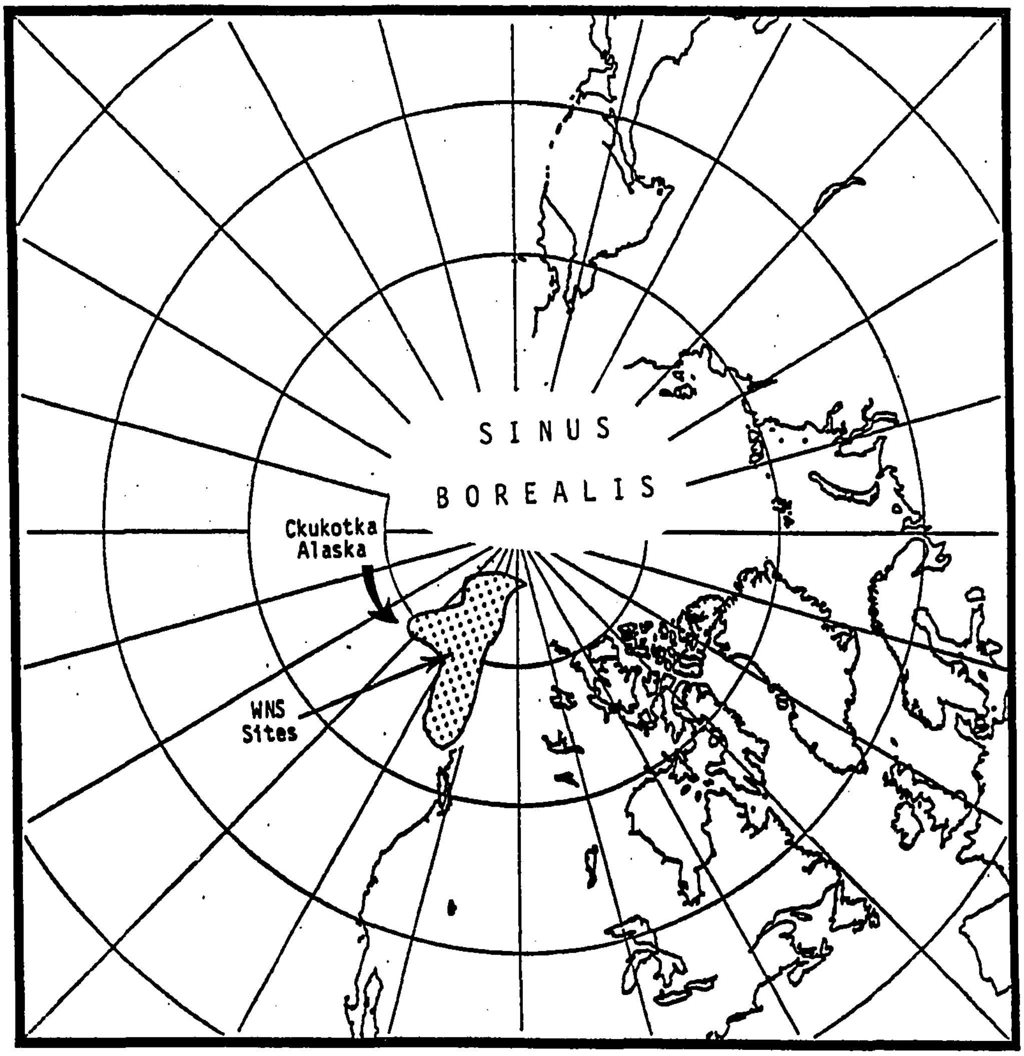


Figure 32. One possible position of Chukotka-Alaska at about the beginning of Late Cretaceous time consistant with the paleolatitude estimate from this paleomagnetic study and assuming Chukotka-Alaska was adjacent to North America in the early Late Cretaceous. Present shorelines are shown only to aid the reader. The major cratonic blocks have been rotated into their positions at about the close of the Early Cretaceous.

arguments in his reconstruction but unless the northward drift of Chukotka-Alaska can be delayed until the early Late Cretaceous then Jones's model and the data presented here are incompatible.

Non-rotational models do have an advantage over the rotation hypothesis with respect to timing. The rotation is more or less constrained to be completed by Neocomian time in order to collide Chukotka-Alaska with interior Alaska and produce the Brookian Orogeny. By strike-slipping Chukotka-Alaska along the Tintina Fault, however, one avoids this constraint. The collisional Brookian event could have begun while Chukotka-Alaska was still at a southerly position in the Early Cretaceous. Chukotka-Alaska was then pushed northward through the Late Cretaceous and rotated counter-clockwise, albeit rapidly. It is only with this significant change in Jones's timing that his model can be made compatible with the paleomagnetic and paleobotanical data presented here.

The last model considered for the tectonic evolution of Chukotka-Alaska is that of Churkin and Trexler (1980). Churkin and Trexler involve a larger system than either Jones's (1980) model or rotation hypotheses (Tailleur, 1973; Newman et al., 1977; Grantz et al., 1979) consider. They start with the movements and positions of the cratonic massifs of the Siberian Platform and North America derived mainly from the opening of the Atlantic in the Mesozoic and Cenozoic and then consider the motions of the tectonostratigraphic terranes that form the remainder of the system.

Churkin and Trexler believe the widened Sinus Borealis allowed oceanic crust of the Kula Plate to extend from the northern Pacific into the proto-Arctic Ocean. This allows them to dismiss the oceanic rises of the Canada Basin, such as the Alpha-Mendeleyev and Chukchi Rises, as remnant oceanic features of the Kula plate unrelated to the evolution of the Canada Basin system. The oceanic features preserved in the Canada Basin are probably the non-collisional analogs of accreted terranes of oceanic affinity (Ben-Avraham, 1981). These Arctic Ocean features simply made it into the Sinus Borealis before the opening of the Atlantic and the arrival of the continental blocks of Kolyma and Chukotka-Alaska closed the passage. If large areas of Kula Plate were consumed in the Sinus Borealis then the Alpha-Mendeleyev rise might be the remnant of a paleosubduction zone (Herron et al., 1974).

It is interesting that Churkin and Trexler's (1980) synthesis does not confront the problem which prompted Tailleur (1973) to propose large-scale micro-continent movements in the Canada Basin: The sedimentary polarity and provenance of the Paleozoic and early Mesozoic northern Alaskan Basin indicate a highlands with continental affinities to the present North. Figure 33 shows Churkin and Trexler's paleogeographic reconstruction for the Early Jurassic. The peninsular position of the Chukotka-Alaska plate does not bring northern Alaska proximal to any suitable source for Paleozoic and early Mesozoic clastics. Within the framework of this model the only other possible source for those sediments is the Chukotka-Alaska plate itself. Previously unrecognized uplift and perhaps orogeny within the Barrovia

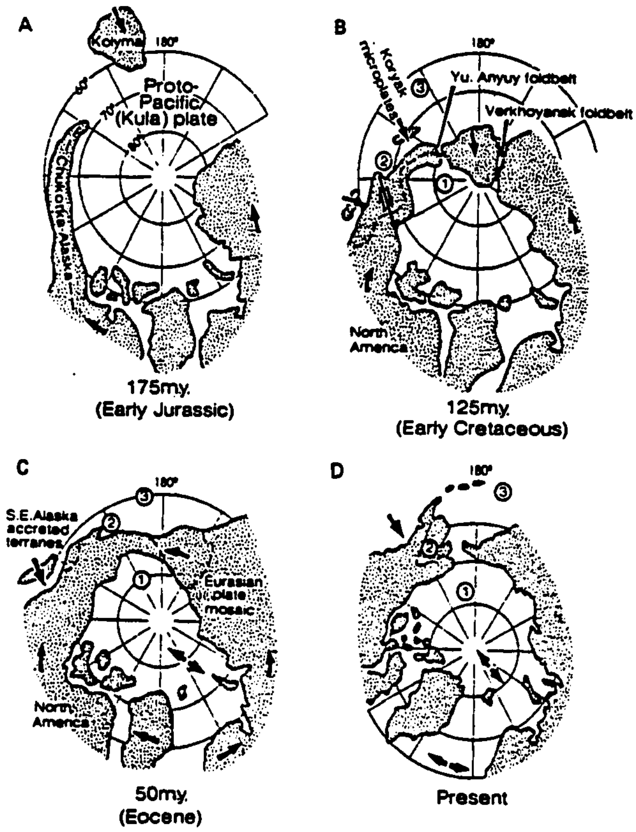


Figure 33. Evolution of the Arctic tectonic system as proposed by Churkin and Trexler, 1980.

region could have provided the source for those sediments.

The paleomagnetic data and the paleontological interpretations are somewhat incompatible with Churkin and Trexler's reconstruction. The problem once again is timing; unless Churkin and Trexler are willing to delay the strike-slip northward movement of the Chukotka-Alaska plate until Late Cretaceous the paleolatitude of the study area predicted from the model does not match the data presented here. If the preliminary paleomagnetic data from the Ruby Geanticline is correct (Plumley and Coe, 1982), and parts of interior Alaska have been in place since the Paleozoic, then Churkin and Trexler's model is more tenable than that of Jones. Jones's model requires that virtually all of interior Alaska was not in place at the end of the Paleozoic.

CONCLUSIONS

Preferred Interpretation of the Data

Paleomagnetic and paleobotanic data both indicate that extreme northwestern Alaska was at a lower paleolatitude in the early Late Cretaceous than most accepted plate tectonic reconstructions suggest. Most incompatible with these interpretations is the rotation hypothesis (Tailleur *et al*., 1973; Newman *et al*., 1977; Grantz *et al*., 1979) which seems to demand Chukotka-Alaska in place by Neocomian time. Two other reconstructions (Jones, 1980; Churkin and Trexler, 1980) are perhaps less specific in their timing arguments and might possibly be modified to fit these data by concentrating the bulk of

Chukotka-Alaska's northward motion in the latest Cretaceous. This modification is geophysically feasible (demanding approximately 2.9 centimeters per year northward translation); however, it may not be justifiable within the geologic constraints of the Alaskan tectonic system.

If, however, the mean geomagnetic dipole did not coincide with the rotational axis or if nondipolar terms of the field were considerably more significant than they are today or in the recent past (Irving, 1964; McElhinney, 1973), then the paleomagnetic interpretations of paleolatitude are in error. This does not seem to be the case, however. Many Cretaceous paleomagnetic studies have shown that the Cretaceous period was fairly quiet with respect to secular variation and reversals. McElhinney (1973) and Irving (1979) both show a_{95} confidence intervals of less than 5 degrees for the Cretaceous. This lack of scatter among Cretaceous pole determinations from all over the Earth justifies the assumption of low secular variation and a predominantly dipolar field in the Cretaceous.

Similarly the paleomagnetic data may have perhaps introduced inclination errors of two kinds: First the bedding horizons interpreted as ancient horizontal might have had considerable original dip; and second, the magnetic grains might have been systematically rotated out of alignment with the geomagnetic field during deposition or diagenesis. It is doubtful whether either type of inclination error contributed significantly to the paleomagnetic interpretations mainly because the samples collected were taken from sections representing diverse flow regimes and paleotransport directions.

Alternative Interpretations

That broad-leaved evergreen plants are limited to less than about 60 degrees latitude in the present 23 degree obliquity regime seems to be fairly well accepted among phytogeographers (Allard, 1948; Wolfe, 1978). This apparently leaves us with the choice of either moving the Chukotka-Alaska plate some 2000 kilometers to the south or allowing the inclination of the Earth's spin axis to vary between 5 degrees and 30 degrees throughout the Late Mesozoic and Cenozoic. Two mechanisms for this variation of spin axis are possible. The inclination variation might have been caused by multiple close approaches of large astronomical bodies or by the oscillation of the Earth's orbital parameters far in excess of that observed today.

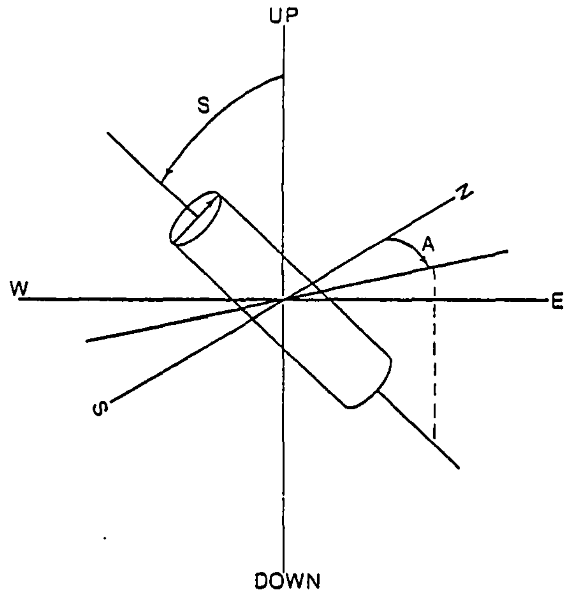
The close approach of a large mass to the Earth several times in a 40 million year period is quite improbable. The frequencies of close approaches are inversely related to the size of the body (Silver et al., 1982). To significantly affect the rotational inertia of the Earth the disturbing mass would have to have had a significant fraction of the Earth's mass. Several collisions might be expected if near misses with massive bodies were common but the geologic record does not show a record of collisions with suitably massive objects. The second possibility is much more plausible; presently the Earth's obliquity (the angle between the spin axis and the normal to the orbit plane) oscillates approximately 2 degrees and the obliquity of Mars varies 20.6 degrees due to resonance between orbital perturbations and rotational precession (Ward, 1973, 1974a, 1974b). As the Earth-Moon system evolved it is possible that the resonance was stronger and resulted in large obliquity oscillations. Ward (1974a) points out that these oscillations would significantly alter the latitudinal distribution of insolation as well as the average daily insolation. Although the possibility of major obliquity oscillations exists for the Earth, the history of the Earth-Moon system is not known in sufficient detail to calculate the past obliquity oscillations.

Two independent data sets have been presented; one geophysical the other paleontological, and both are consistent with approximately 15 degrees northward drift of Chukotka-Alaska during the latest Cretaceous. Both data sets admit the possibility of alternative hypotheses but another new hypothesis is needed to explain each of the lines of evidence. Paleomagnetic inclination errors or anomalous secular variation will not allow broad-leaved evergreens to grow at high latitudes nor will obliquity oscillations create shallow paleomagnetic inclinations. To invoke two new hypotheses in order to explain these observations seems unnecessary in this case; rather the northward drift of Chukotka-Alaska, in the manner proposed by Jones (1980) or Churkin and Trexler (1980), seems the most logical explanation.

Unfortunately both data sets deal only with an instant of time approximately 100 million years ago. In order to properly understand the evolution of the Arctic Ocean and arctic Alaska a knowledge of arctic Alaska'a paleolatitude through time is necessary. Further paleomagnetic sampling is needed from outcrop sections; and if possible, from the subsurface. Perhaps more modern thermal demagnetization techniques and sensitive magnetometers will allow paleomagnetism to see through the Brookian Orogeny overprint that has apparently imposed a later steep magnetization on many northern Alaskan rocks (Newman et al., 1977; Hillhouse and Gromme, 1981).

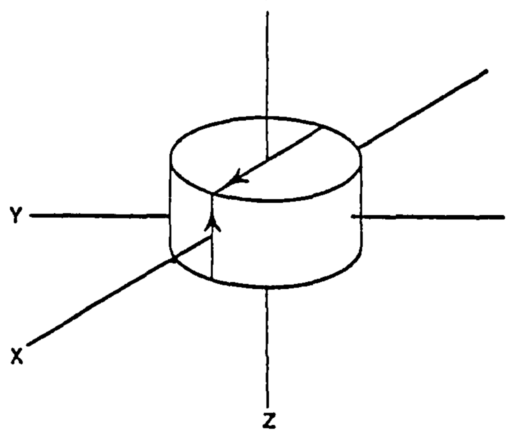
Appendix A

Geometric relationships between and within the core, geographic and stratigraphic frames of reference.



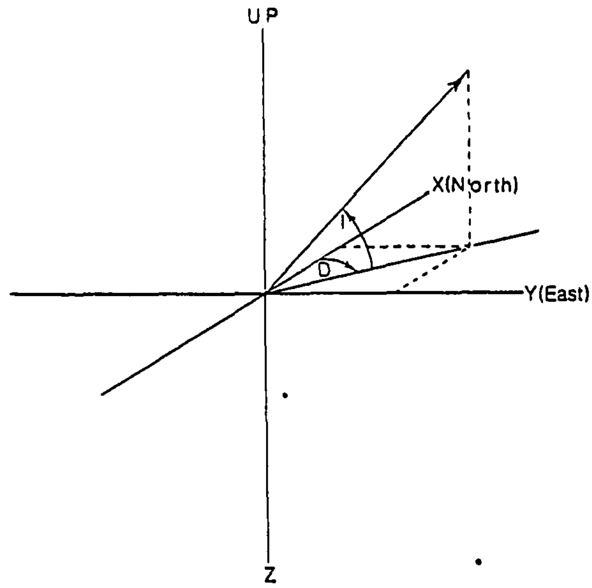
Core Orientation Conventions

A-Azimuth of core axis (0°-360°) measured from north.
S-Dip of core axis (-90°-+90°, positive as shown) from horizontal.



Core Coordinate System
Positive axes shown.

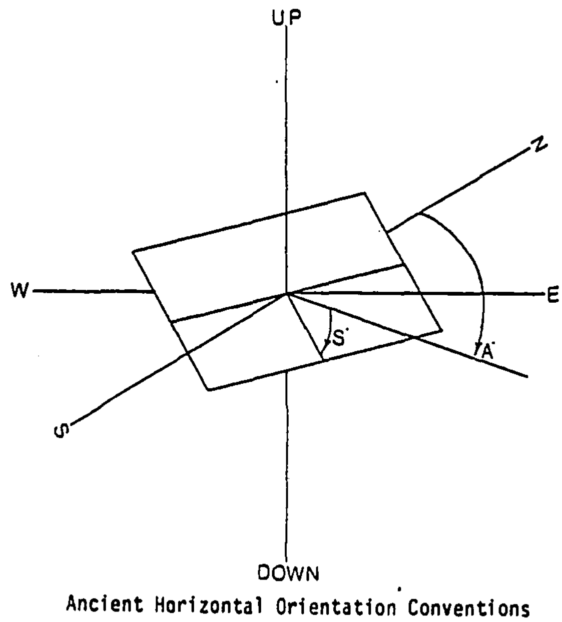
Figure A1. Core orientation and core coordinate systems.



Magnetization Vector Orientation Conventions

D-Declination measured from true north (0°-360°), +X is north, +Y is east, +Z is down.

I-Inclination measured from horizontal (-90°-+90°), positive downwards.



Ancient Horizontal Orientation Conventions

A'-Azimuth of dip direction of ancient horizontal plane measured from north (0°-360°).
S'-Dip of ancient horizontal plane (-90°-+90°), positive downwards.

Figure A2. Magnetic vector and ancient horizontal coordinate systems.

Appendix B

Tables B1 through B13 and Figures B1 through B13 show the specimen number, remnant magnetization in the geographic and stratigraphic frames of reference, as well as the level at which a stable magnetic direction was picked. The "status" column indicates whether the datum was selected or rejected. If rejected, the specific criterion for rejection is also indicated.

Table B1

Site WNS-01 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
Reject Theta>50°	1A	137, 39	137, -1	450
	2A	161, 40	155, 2	450
Reject Theta>50°	3A	248, 45	263, 38	450
	4A	123, 73	071, 80	450
	Mean	167.9, 59.1	163.8, 42.8	
	N	4	4	
	k	5.2	1.9	
	a_{95}	30.8	51.4	

Theta = 50°

Site Rejected k_2,k_1

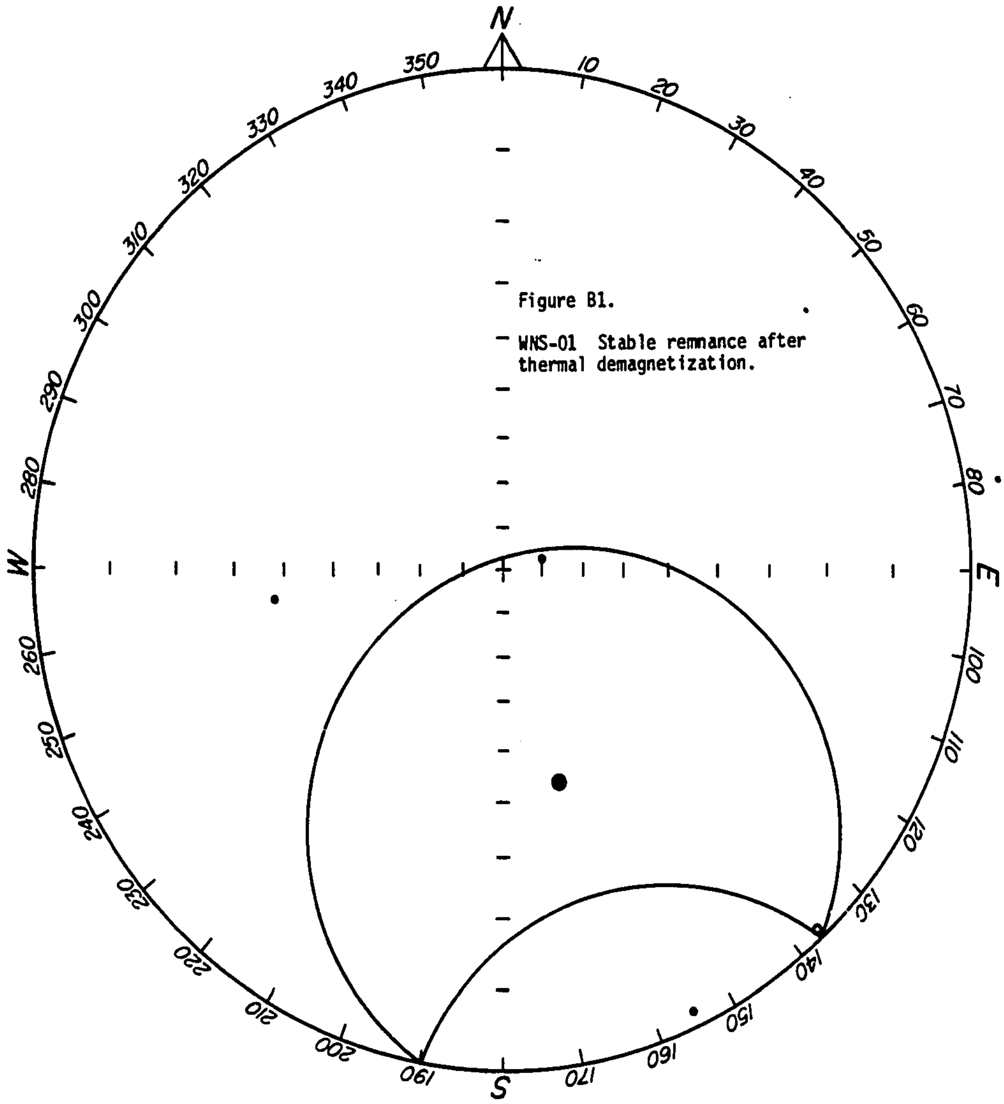


Figure B1.

WNS-01 Stable remmance after thermal demagnetization.

Table B2

Site WNS-02 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	195, 45	195, 81	350
	2A	161, 53	027, 74	300
	3A	154, 76	016, 52	350
	4A	207, 57	330, 68	300
	5A	229, 40	277, 35	300
	6A	182, 66	016, 65	300
	7A	056, 53	036, 25	300
	8A	160, 49	102, 74	300
Reject Theta>71.8°	9A	044, 03	052,-33	300
	10A	180, 58	032, 76	300
	11A	242, 71	332, 66	300
	12A	279, 79	353, 44	300
	13A	167, 69	051, 84	300
	14A	173, 76	246, 88	300
	Mean	174.3, 71.1	010.3, 68.8	
	N	14	14	
	k	5.8	4.9	
	a_{95}	15.6	17.0	

Theta = 71.8°

Site Selected

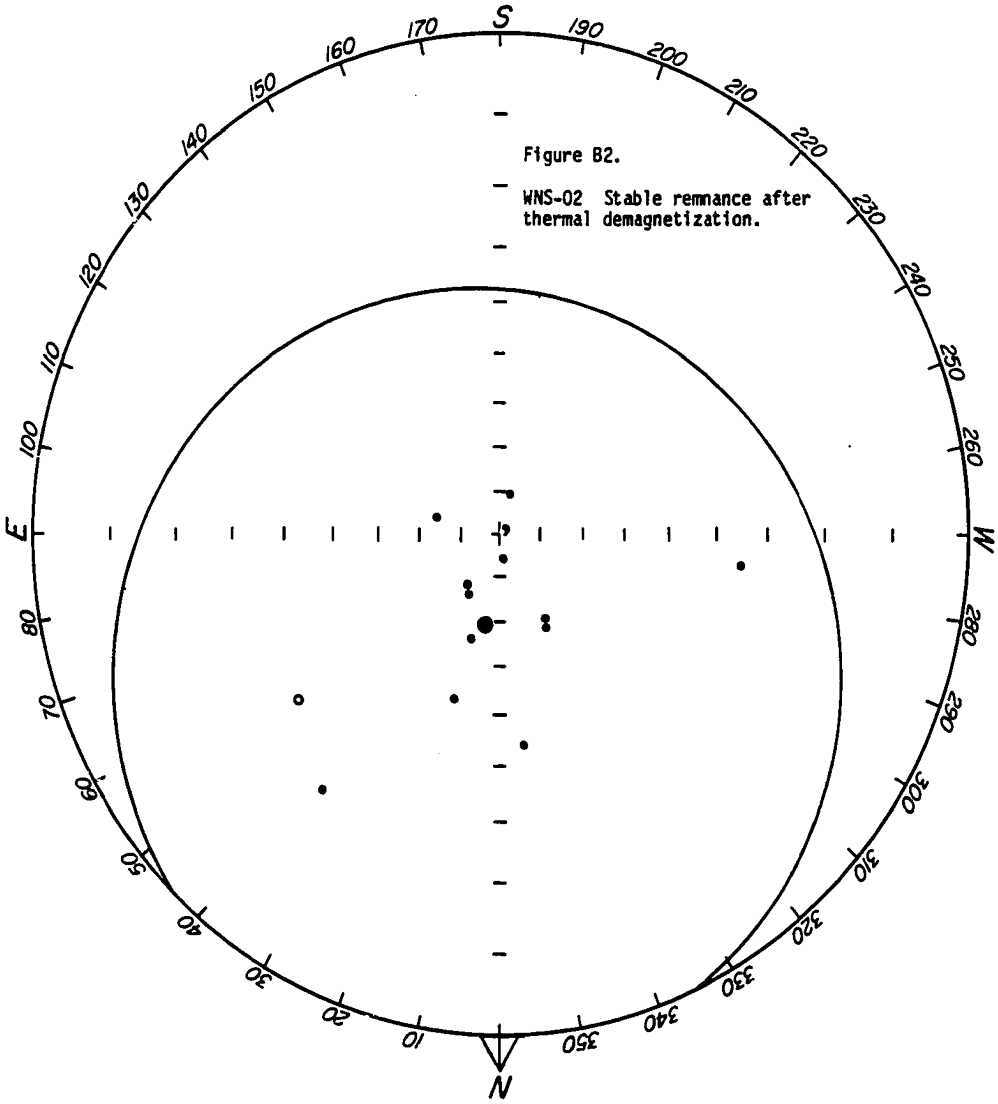


Figure B2.

WNS-02 Stable remnance after thermal demagnetization.

Table B3

Site WNS-03 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	175, 68	294, 62	400
	2A	102, 20	084, 42	250
	3A	220, 70	289, 55	300
	4A	288, 50	301, 28	400
	5A	111, 80	350, 70	400
	6A	021, 73	000, 55	300
	7A	326, 28	328, 09	250
	8A	027, 82	354, 64	400
	Mean	354.3, 86.1	332.4, 58.3	
	N	8	8	
	k	4.3	5.2	
	a_{95}	23.7	21.8	

Theta = 73.7°

Site Selected

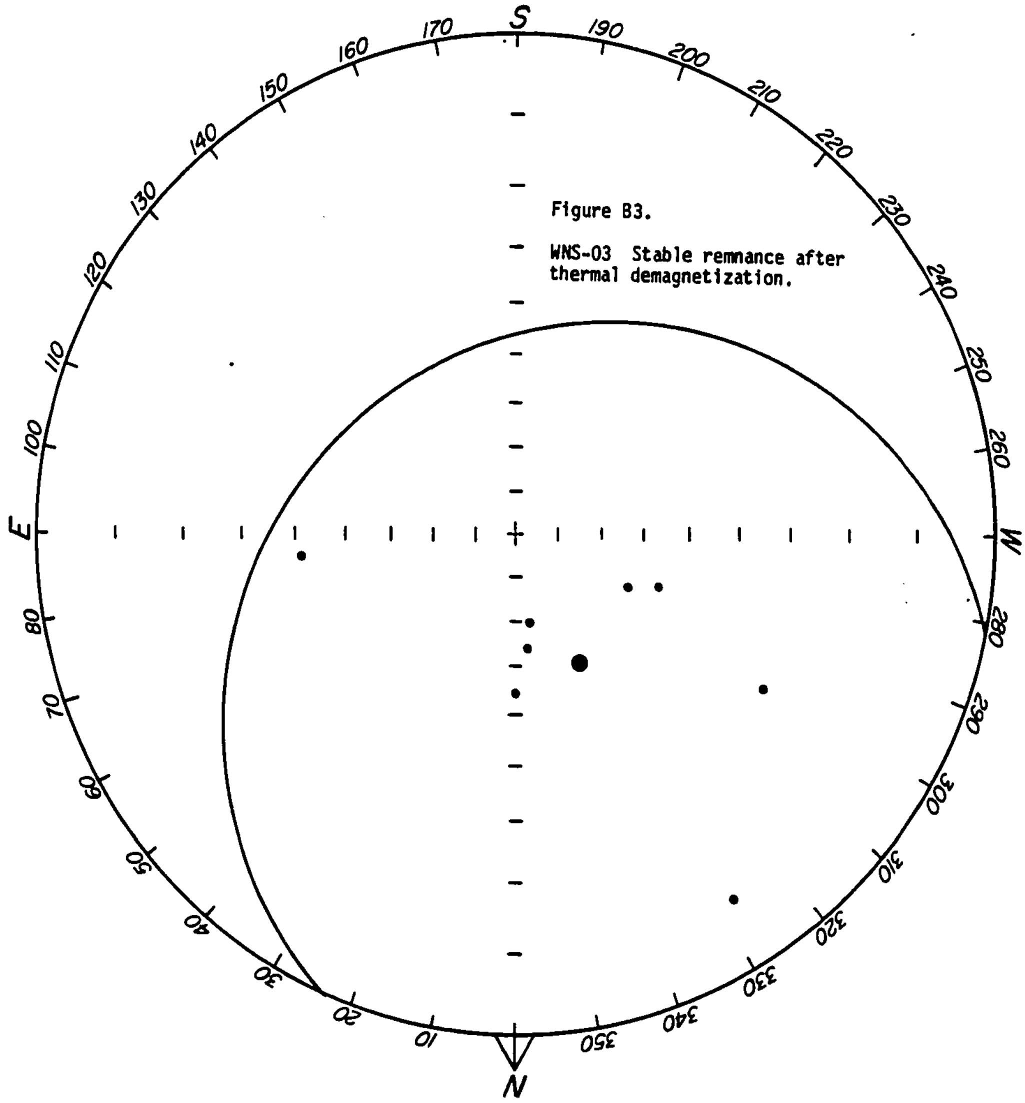


Figure B3.

WNS-03 Stable remnance after thermal demagnetization.

Table B4

Site WNS-04 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	130, 74	160,-17	400
	2A	136, 68	157,-23	500
Reject Theta>50°	3A	336, 73	174, 77	300
Reject Theta>50°	4A	003, 57	065, 80	300
	5A	167, 62	163,-25	400
Reject Theta>50°	6A	135, 31	127,-50	500
Reject Azbed, dipbed error	7A	168, 25	168, 25	300
Reject Azbed, dipbed error	8A	175, 32	175, 32	300
	Mean	122.6, 75.7	152.4, 1.4	
	N	6	6	
	k	6.6	2.0	
	a_{95}	22.2	40.0	

Theta = 50°

Site Rejected N<4

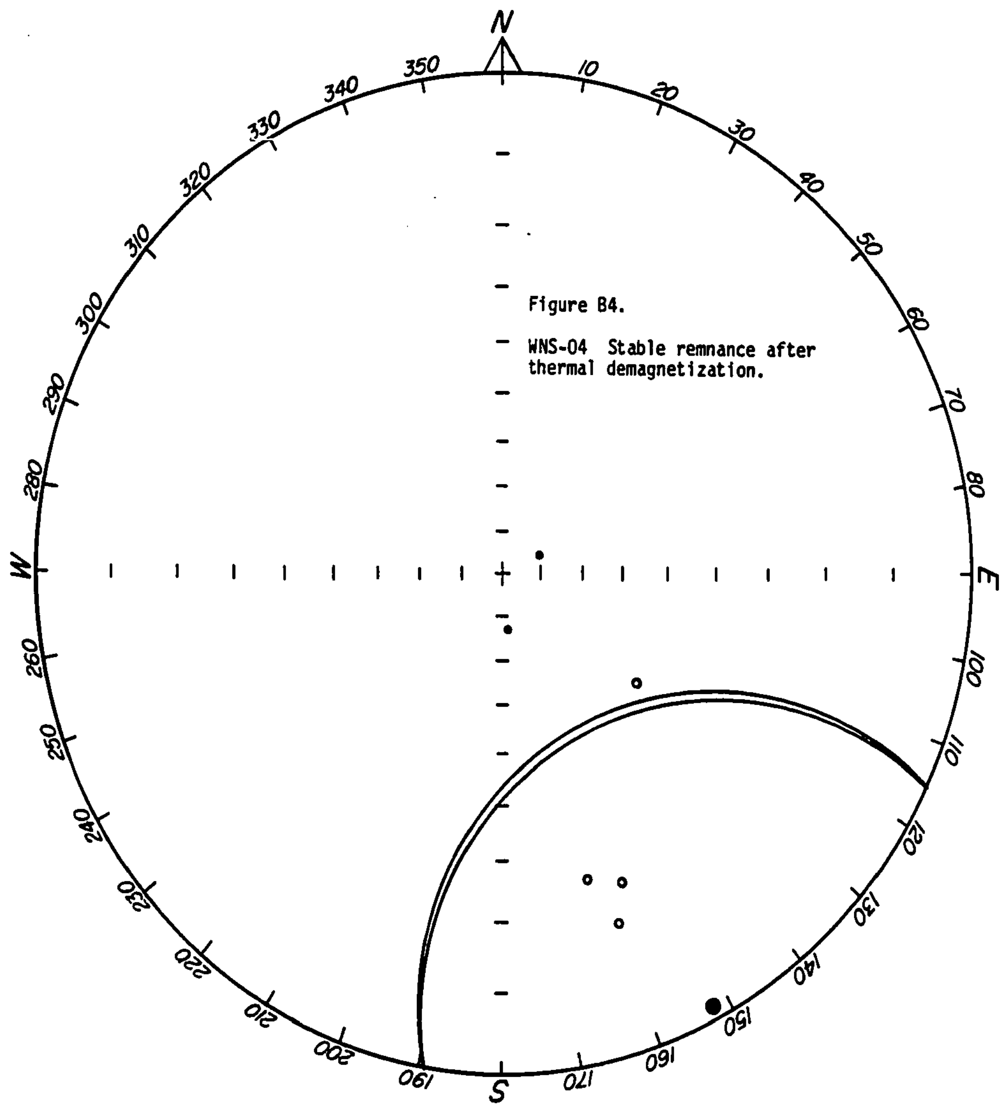


Figure B4.

WNS-04 Stable remnance after thermal demagnetization.

Table B5

Site WNS-05 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
Reject Theta>50°	1A	116, 07	103,-32	250
	2A	333, 68	176, 68	300
Reject Theta>50°	3A	026,-20	239, 66	300
Reject Theta>50°	4A	308, 48	239, 66	200
	Mean	27.7, 48.0	83.2, 59.0	
	N	4	4	
	k	1.5	1.4	
	a_{95}	57.9	60.1	

Theta = 50°

Site Rejected N = 1

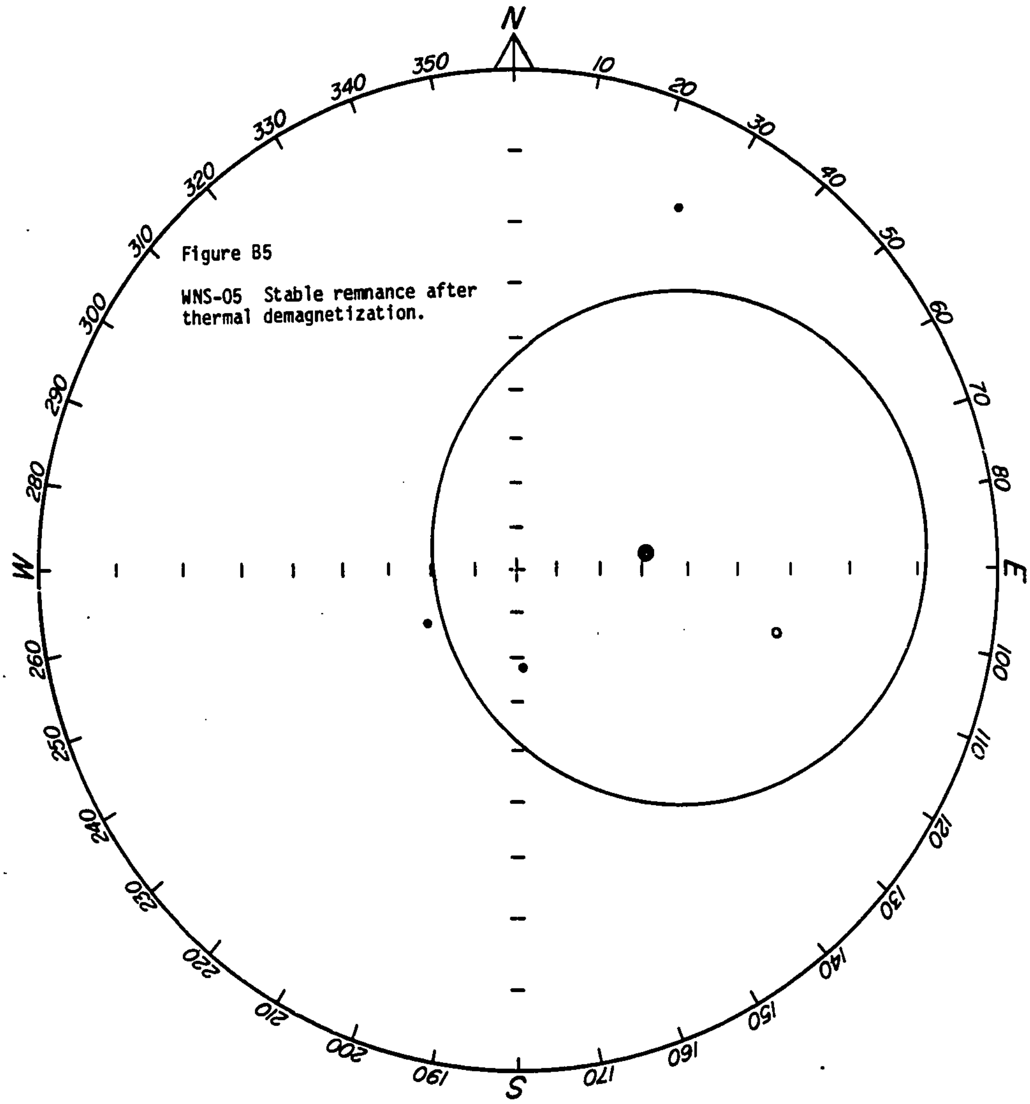


Figure B5

WNS-05 Stable remnance after thermal demagnetization.

Table B6

Site WNS-06 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	24, 49	197, 72	400
Reject Theta>29.6°	2A	15, 18	356, 75	400
	3A	357, 62	232, 63	350
	4A	343, 40	268, 70	400
	5A	001, 44	196, 68	400
	6A	344, 41	226, 64	400
	7A	355, 51	199, 60	400
	8A	023, 57	171, 70	450
	9A	003, 53	209, 74	450
Reject Azbed, dipbed error	10A	026, 81	195, 39	450
	Mean	2.5, 47.1	215.7, 73.2	
	N	9	9	
	k	24.3	27.8	
	a_{95}	9.5	8.8	

Theta = 29.6°

Site Selected

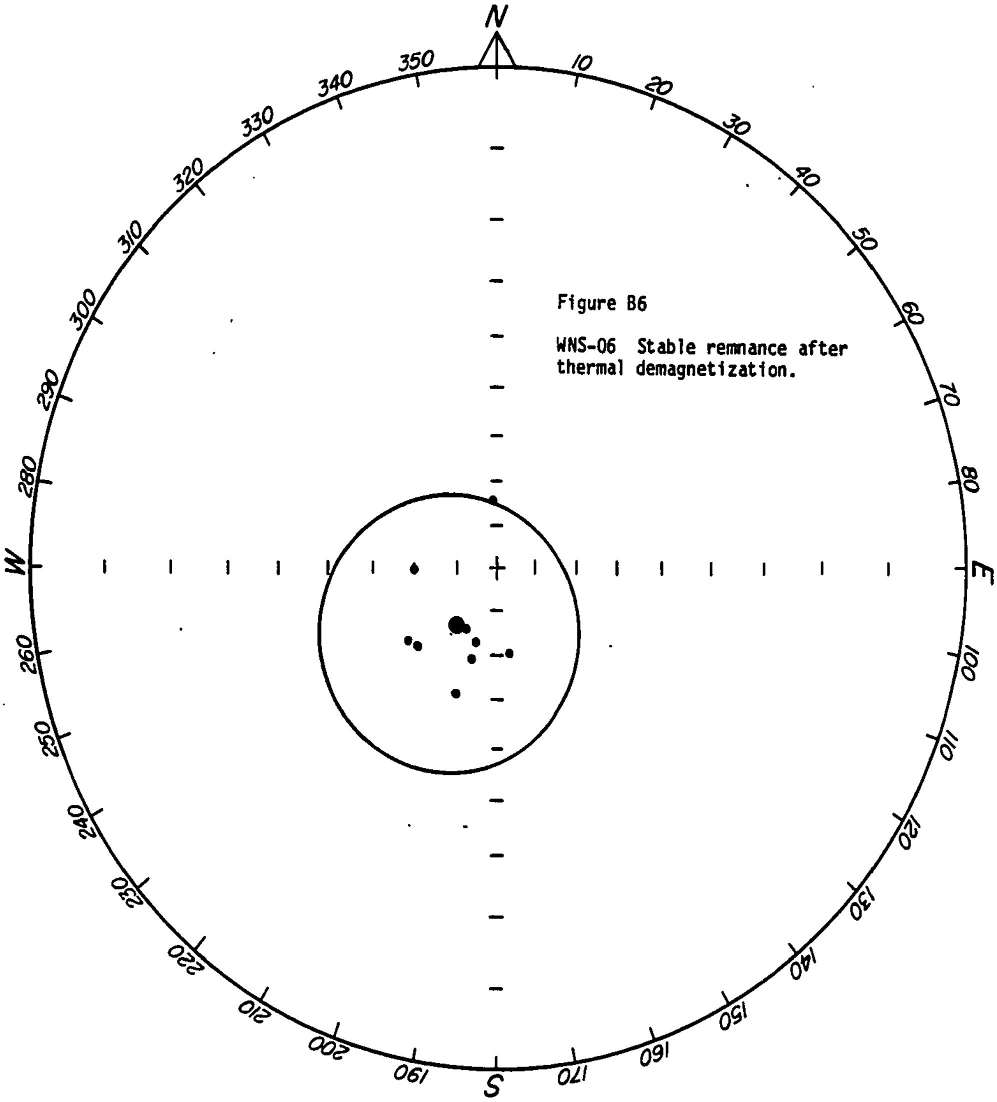


Figure B6

WNS-06 Stable remnance after thermal demagnetization.

Table B7

Site WNS-07 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	005, 50	289, 75	300
Reject Theta>67.2	2A	273, 02	277,-14	300
	3A	034, 60	181, 66	300
	4A	017, 66	201, 62	300
	5A	114, 81	187, 34	400
	6A	018, 62	176, 66	300
	7A	015, 62	204, 67	300
	8A	011, 73	204, 60	300
	9A	missing ----------------------------		
	10A	083, 80	179, 54	300
	11A	005, 60	332, 76	300
	12A	017, 62	350, 81	450
	Mean	004.4, 68.3	213.9, 67.7	
	N	11	11	
	k	7.8	5.7	
	a_{95}	15.1	17.7	

Theta = 67.2°

Site Rejected k2<<k1

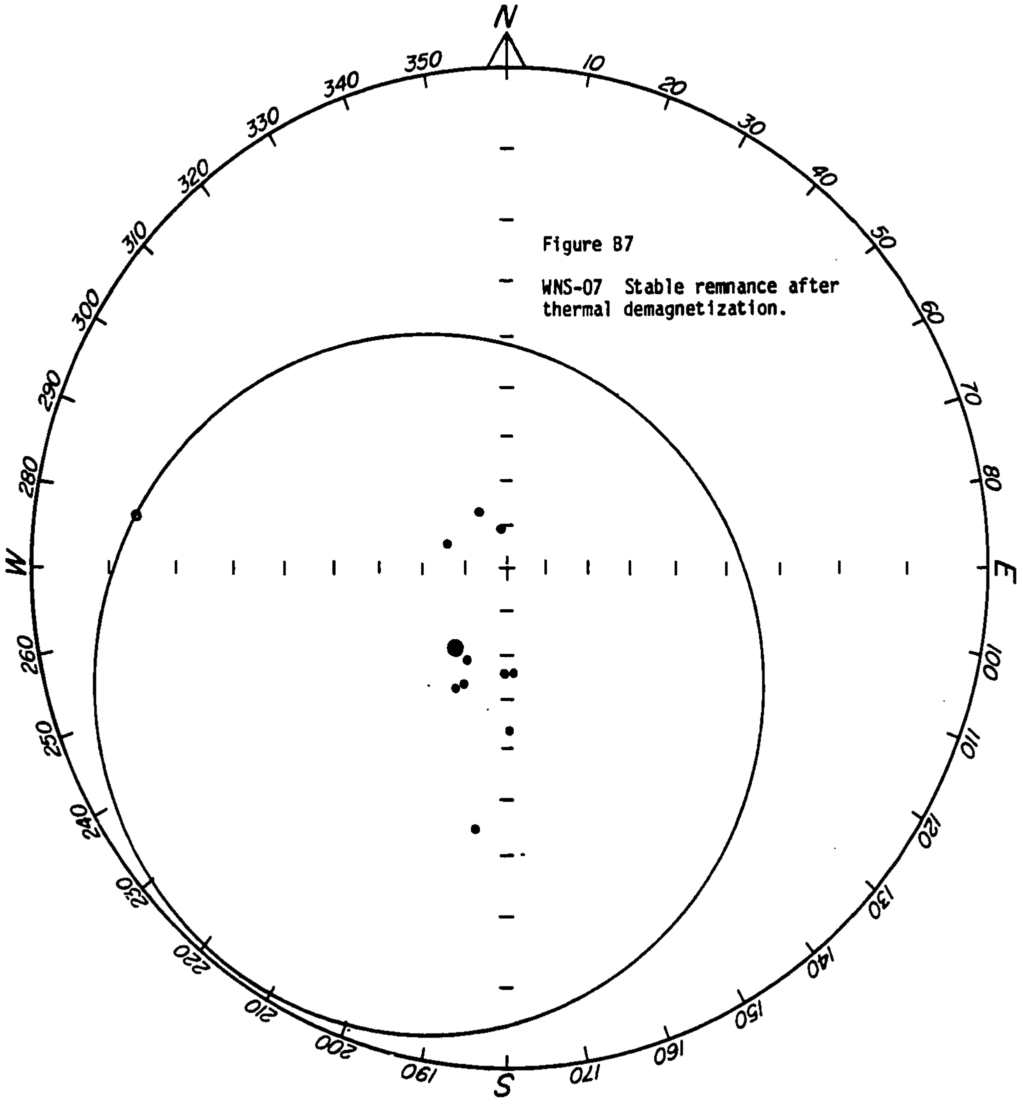


Figure B7

WNS-07 Stable remnance after thermal demagnetization.

Table B8

Site WNS-08 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	266, 42	268,-03	350
	2A	143, 68	220, 46	350
	Mean	235.8, 68.7	248.6, 23.3	
	N	2	2	
	k	3.5	3.2	
	a_{95}	52.9	55.2	

Theta = 50°

Site Rejected k2<5

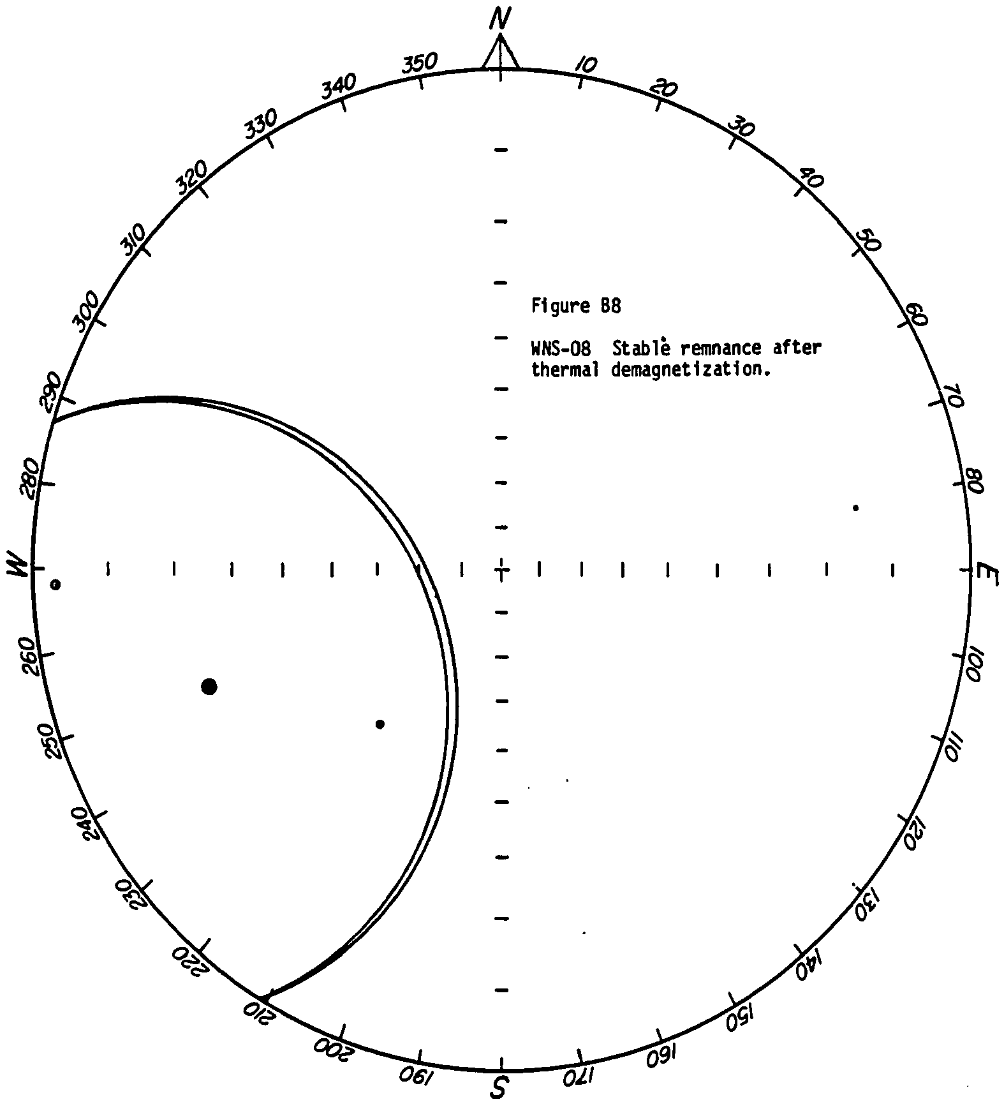


Figure B8

WNS-08 Stablè remnance after thermal demagnetization.

Table B9

Site WNS-09 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	016, 66	322, 81	300
	2A	060, 71	147, 82	450
	3A	229, 33	227, 10	550
	4A	015, 69	308, 67	500
	5A	037, 68	316, 75	400
	6A	046, 69	315, 78	450
	7A	330, 69	276, 73	450
	8A	026, 76	218, 80	450
	9A	099, 64	169, 59	450
	10A	032, 86	199, 82	400
	11A	173, 77	179, 68	450
	12A	060, 80	152, 79	350
	Mean	035.5, 81.8	229.7, 78.8	
	N	12	12	
	k	11.8	10.2	
	a_{95}	11.8	12.6	

Theta = 50°

Site Selected

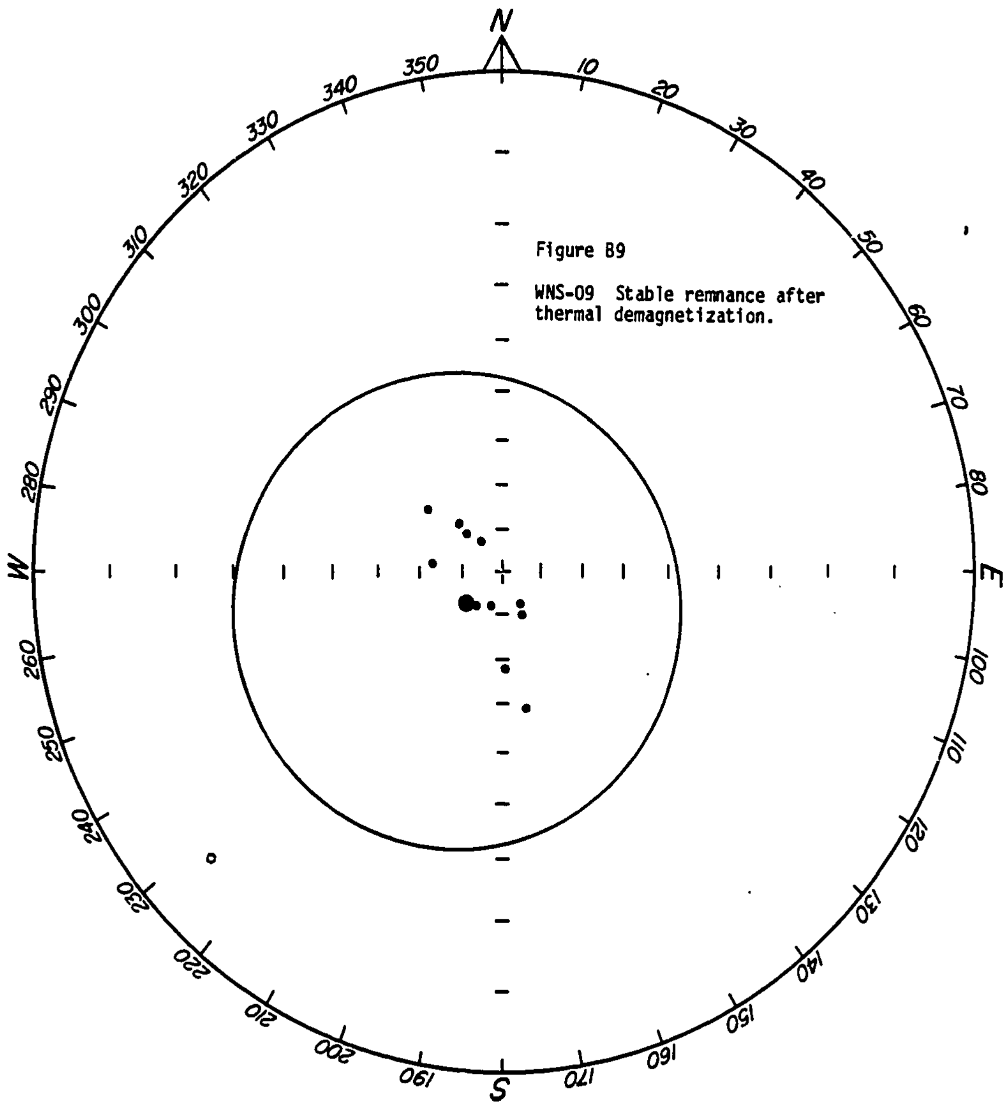


Figure B9

WNS-09 Stable remnance after thermal demagnetization.

Table B10

Site WNS-10 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	146, 85	279, 85	350
	2A	032, 87	325, 80	400
	3A	146, 85	279, 85	350
	4A	255, 69	219, 75	350
	5A	270, 79	303, 84	350
	6A	189, 79	148, 82	350
	7A	222, 72	212, 79	400
	Mean	226.7, 82.6	245.2, 85.0	
	N	7	7	
	k	58.1	93.8	
	a_{95}	6.9	5.5	

Theta = 16.5°

Site Selected

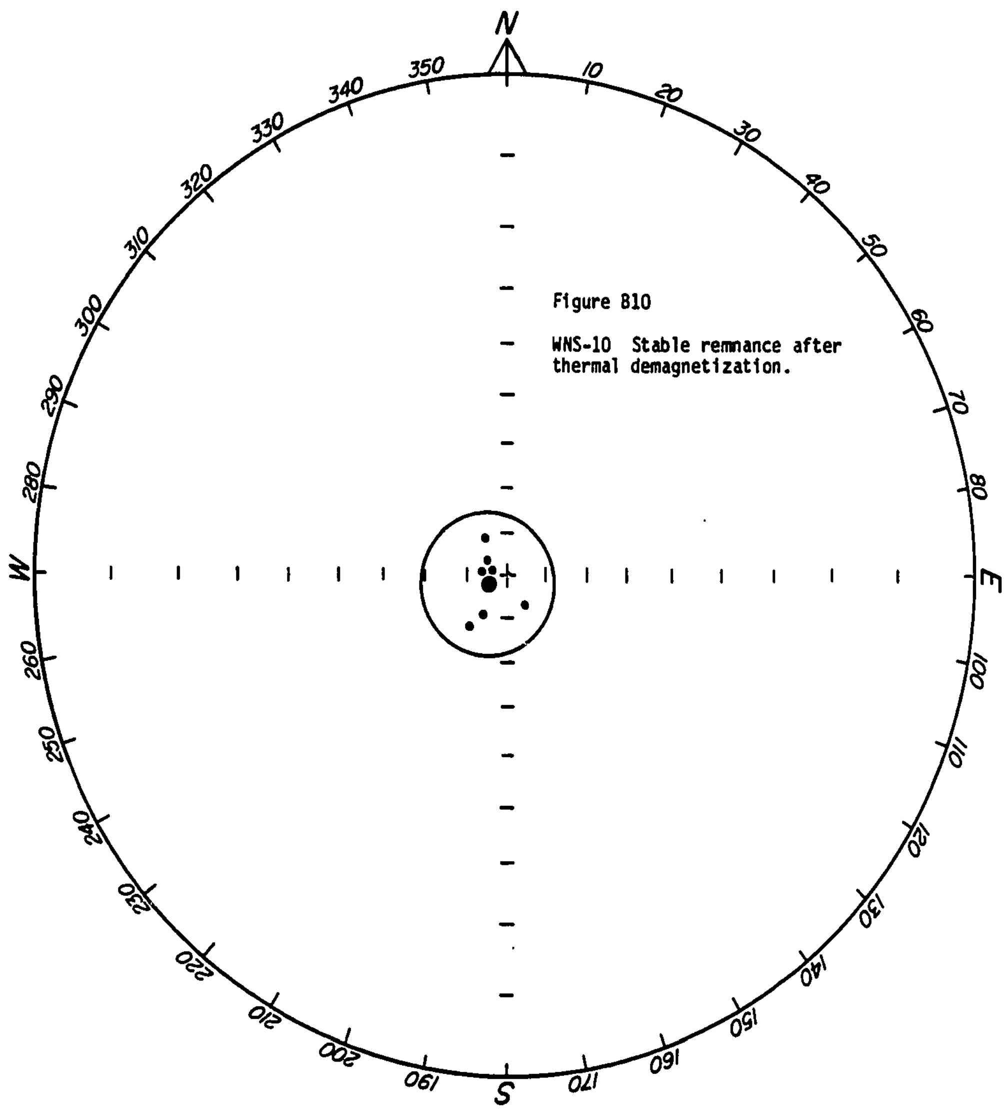


Figure B10

WNS-10 Stable remnance after thermal demagnetization.

Table B11

Site WNS-11 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	118, 69	339, 78	350
	2A	110, 71	340, 74	450
Rejected Theta>33.3°	3A	198, 33	222, 40	350
	4A	100, 75	347, 78	450
	5A	123, 67	037, 88	450
	6A	131, 74	305, 83	450
	7A	126, 50	122, 70	350
	8A	163, 57	219, 71	350
	9A	145, 52	174, 76	450
	10A	171, 77	319, 74	450
	11A	179, 77	291, 74	350
	12A	134, 60	182, 88	350
	13A	150, 60	220, 81	350
	14A	141, 73	280, 80	350
	15A	155, 72	308, 76	350
	16A	123, 46	106, 70	350
	17A	171, 58	213, 66	450
	Mean	145.5, 65.5	248.2, 84.3	
	N	17	17	
	k	22.2	20.1	
	a_{95}	7.2	7.6	

Theta = 33.3°
Site Selected

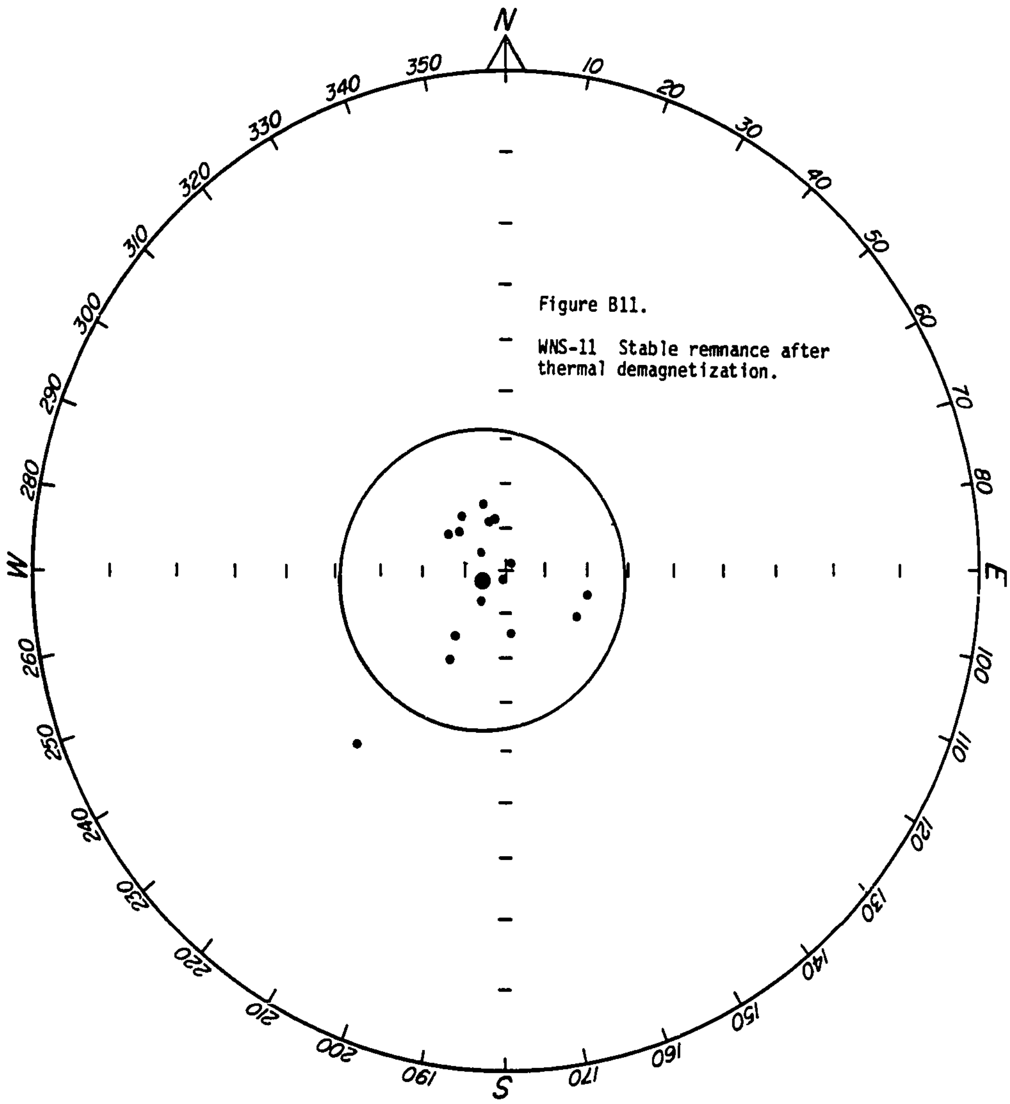


Figure B11.

WNS-11 Stable remnance after thermal demagnetization.

Table B12

Site WNS-12 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	017, 61	139, 71	450
	2A	020, 52	111, 73	450
	3A	333, 43	273, 74	350
	4A	201, 53	004, 82	350
	5A	207, 44	282, 83	450
	6A	222, 44	294, 73	350
	7A	184, 40	316, 74	350
	8A	147, 62	012, 57	450
	9A	169, 30	145, 81	450
	10A	168, 33	081, 85	450
	11A	186, 67	343, 59	450
	12A	160, 35	041, 65	350
	13A	161, 18	083, 72	350
	14A	168, 24	095, 80	450
	15A	161, 44	019, 72	350
	16A	164, 24	081, 62	450
	17A	231, 38	300, 47	450
	18A	182, 44	324, 69	450
	19A	182, 36	306, 76	450
	20A	210, 62	330, 43	350
	21A	194, 40	275, 73	250

Table B12 cont'd.

Site WNS-12 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	Mean	181.7, 52.7	350.2, 80.5	
	N	21	21	
	k	5.6	14.9	
	a_{95}	12.9	7.9	

Theta = 38.5°

Site Selected

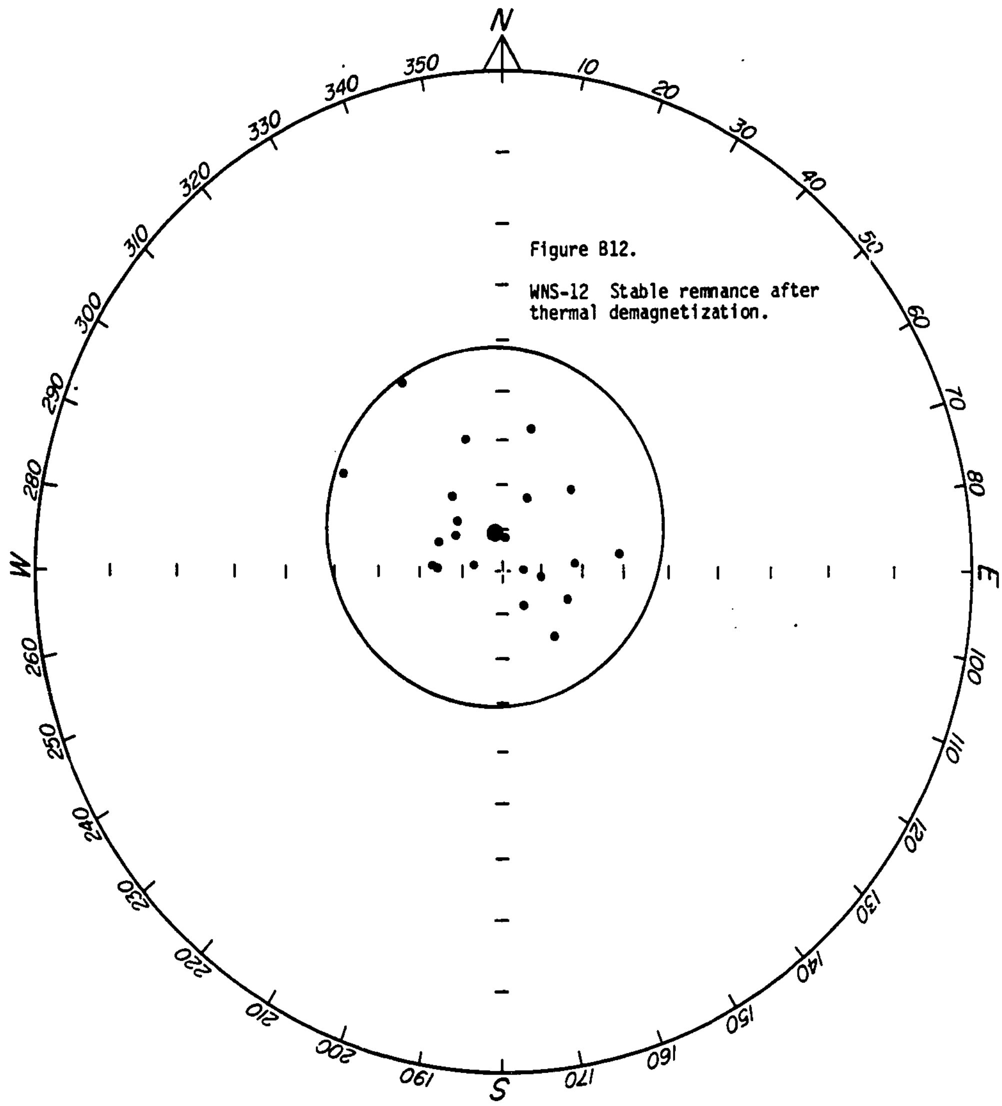


Figure B12.

WNS-12 Stable remnance after thermal demagnetization.

Table B13

Site WNS-13 Thermal Demag

Status	Specimen #	Geographic	Stratigraphic	°C Level
	1A	207, 81	309, 80	450
	2A	243, 86	329, 75	450
	3A	327, 80	337, 65	350
	4A	235, 76	298, 79	450
	5A	338, 81	329, 76	350
	6A	323, 82	320, 76	500
	7A	248, 71	271, 60	350
	8A	274, 84	296, 70	350
	9A	249, 72	273, 61	450
	10A	089, 66	028, 82	450
	11A	032, 66	011, 62	350
	12A	057, 81	359, 78	350
	13A	010, 81	338, 73	350
	14A	328, 77	322, 66	350
	Mean	317.2, 86.3	319.3, 74.5	
	N	14	14	
	k	33.8	40.3	
	a_{95}	6.4	5.9	

Theta = 23.6°

Site Selected

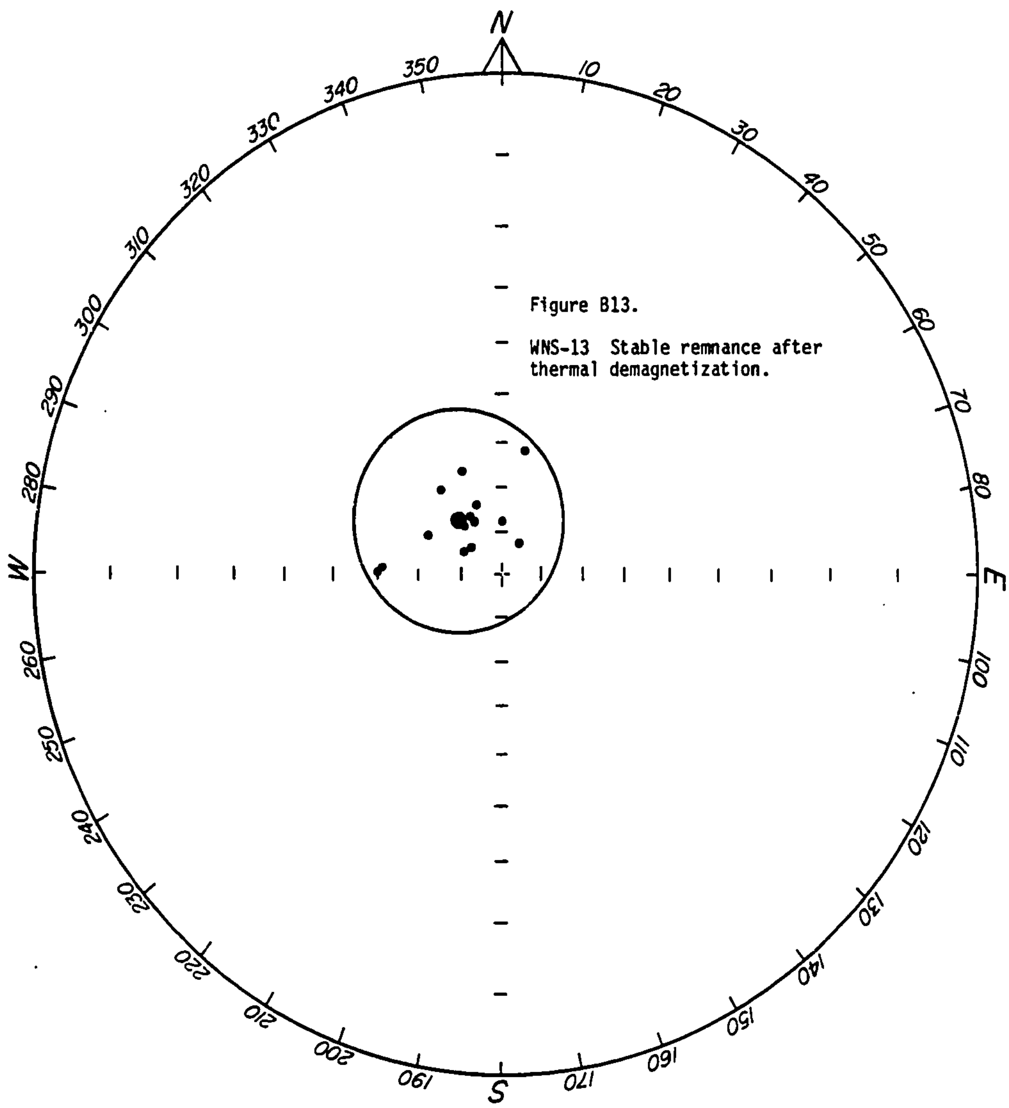


Figure B13.

WNS-13 Stable remnance after thermal demagnetization.

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